United States
Department of
Agriculture

Agricultural Research Service

ARS-38

June 1985

ARS Wheat Yield Project

ABSTRACT

Willis, W.O., Project Coordinator. 1985. ARS Wheat Project Yields. U.S. Department of Agriculture, Agricultural Research Service ARS-38, 217 p.

The national ARS Wheat Yield project was formally initiated in October 1976 with the objective of developing a concise description of plant response to its environment which would include capability for yield prediction. This document describes some activities and products of the ARS Wheat Yield Group. The products presented here include brief descriptions of (a) project development, (b) data sets developed by measuring soil, plant and climate parameters through complete growth cycles of winter wheat and spring wheat at several locations and years in the Great Plains and Pacific Northwest, (c) dynamic simulation models of wheat growth and yield, and (d) methods for using remotely sensed data to assess plant conditions, provide early warnings of poor (abnormal) growing conditions, and provide surrogate inputs to the plant growth models.

KEYWORDS: winter wheat, spring wheat, yield prediction, simulation growth models remote sensing, early warning, Great Plains, Pacific Northwest

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CONTENTS

Page

Chapter 1. Development of the ARS Wheat Yield Project
W.O. Willis, A.R. Grable 1

Chapter 2. Description of Data Collection Sites and Methods
A. Northern Great Plains: Winter Wheat
J.K. Aase, A.L. Black 5

B. Central Great Plains: Winter Wheat
D.E. Smika 14

C. Southern Great Plains: Winter Wheat
J.T. Musick, D.A. Dusek 18

D. Pacific Northwest: Winter Wheat
R.E. Ramig, R.W. Rickman 27

E. Northern Great Plains: Spring Wheat
A. Bauer, J.K. Aase 42

Chapter 3. Climatic Data Acquisition
H.R. Duke, M.C. Blue 62

Chapter 4. Processing of Meteorological Data from Field Sites in the Central Great Plains
D.F. Heermann, P.F. Williams, K.M. Stahl 80

Chapter 5. Development of Agrometeorological Model Inputs from Remotely Sensed Information
C.L. Wiegand, L.F. Lautenschlager, P.J. Pinter, Jr., J.K. Aase, R.D. Jackson, J.E. McMurtrey, III, A.J. Richardson, D.E. Smika 95

Chapter 6. Plant Stress and Stress-Yield Relationships Determined Using Remotely Sensed Data
R.D. Jackson, R.J. Reginato, S.B. Idso, P.J. Pinter, Jr. ... 108

Page

Chapter 7. Description of MSS Data
L.F. Lautenschlager 127

Chapter 8. Physiological and Phenological Research in Support of Wheat Yield Modeling
B. Klepper, A.B. Frank, A. Bauer, J.A. Morgan 134

Chapter 9. SPAR and the Physiological Process Level Model
D.N. Baker, J.E. Parsons, C.J. Phene, J.R. Lambert, J. M. McKinion, H.F. Hodges 151

Chapter 10. Description and Performance of CERES-Wheat: A User-Oriented Wheat Yield Model
J.T. Ritchie, S. Otter 159

Chapter 11. The Development of WINTER WHEAT: A Physical Physiological Process Model
D.N. Baker, F.D. Whisler, W.J. Parton, E.L. Klepper, C.V. Cole, W.O. Willis, D.E. Smika, A.L. Black, A. Bauer 176

Chapter 12. Development of Early Warning Models
G.O. Boatwright, F.W. Ravet, T.W. Taylor 188

Chapter 13. Sensitivity Analysis of Wheat Models
G.A. Larsen 196

Chapter 14. A Summary of Vegetation Indices Developed for Remote Sensing
C.R. Perry, Jr., L.F. Lautenschlager 204

Chapter 15. Application of Wheat Yield Project Information to Foreign Areas
J.L. Rogers 216

245

CHAPTER 1. DEVELOPMENT OF THE ARS WHEAT YIELD PROJECT

W. O. Willis and A. R. Grable[1]

The mid-1970's was a period of declining crop inventories, increasing export demands, and rapidly increasing commodity prices. Russia purchased unusually large amounts of grains to offset their poor harvest in 1972 and prices rose dramatically. A severe drought in 1974 significantly reduced yields of wheat, corn, and soybeans in the United States, and wheat prices reached an all-time high. These events triggered activities such as the World Food Conference held in Rome in 1974 and World Food and Nutrition Study started by the National Research Council in 1975. The USDA, NASA, and other groups started the Large Area Crop Inventory Experiment (LACIE) in 1975 in an effort to develop improved methods for crop forecasting.

During this same period, it was becoming increasingly apparent that the technologies for crop forecasting were nearing the point of practical application. Scientists in ARS and other organizations had demonstrated that process-oriented crop models were technically possible and that the effects of climatic and other variables on crop production could be quantified. Evidence was increasing that remote sensing technologies could be used to gather critical data about the status of crops, weather, and soils. Clearly, improved methods of forecasting crops were needed, and the technologies appeared to be ready.

The following chapters give a synoptic description of the research findings from a project that was unique in several respects. It was the first national project in ARS in which the development of crop simulation models was a specific objective. Scientists and administrators from all four Regions of ARS participated, as did people from other organizations. People from several different scientific disciplines contributed to planning and implementing the project. Such cooperation and coordination were not that common in ARS when the project started, and the project itself became a model for other projects that started later. During the early years of the project, the scientists determined the distribution of funds for specific kinds of work needed to achieve the objectives. The project began during a time of severe budget constraints and illustrates what can be accomplished through a combination of teamwork, innovation, and individual dedication.

In early 1975, T. W. Edminster who was then Administrator of ARS, approved a budget increase proposal of $352,000 for a multilocation project to improve the Department's capability (develop models) for forecasting crop yields. With this funding established, the ARS National Program Staff selected a small multidisciplinary group of ARS scientists who met at Beltsville, Maryland in March 1976 to initiate the project. At their first formal meeting in October 1976, the ARS Crop Yield Group decided that wheat would be the first crop they would address. Thus, this Crop Yield Group became known as the ARS Wheat Yield Group.

Original members of the group were Donald N. Baker (Mississippi State, MS), Alfred L. Black (Sidney, MT, now Mandan, ND), Albert R. Grable (Beltsville, MD now Fort Collins, CO), Dale F. Heermann (Fort Collins, CO), Ray D. Jackson (Phoenix, AZ), Edgar R. Lemon (Ithaca, NY, now retired), William A. Raney (Beltsville, MD, now retired), Joe T. Ritchie (Temple, TX),

[1] Project Coordinator and National Program Leader, respectively, Fort Collins, CO 80522.

Darryl E. Smika (Akron, CO), Craig L. Wiegand (Weslaco, TX), and Wayne O. Willis (Mandan, ND now Fort Collins, CO). Willis was designated as coordinator of the project and has continued in that role.

From that meeting in October 1976 the following objectives emerged:

- Assemble existing data sets on the growth and development of winter wheat.
- Build a field-scale, physiologically based wheat growth model.
- Test the model using independent data sets which include different environmental stresses imposed at different times.
- Develop the capacity of the model to forecast yields from large areas and develop the means to use remotely sensed information in the model, e.g. data from earth orbiting satellites such as LANDSAT.
- Repeat the process for other crops.

All agreed this research should lead to an improved understanding of crop growth, with emphasis on effects of climatic factors. It was planned to include weather probabilities and effects of other stress factors such as insects, diseases, and weeds.

Most of the scientists present at the initial meetings still participate in the ARS Wheat Yield Group. Some of the other ARS scientists who participated or are involved currently are: J. K. Aase (Sidney, MT); Armand Bauer and A. B. Frank (Mandan, ND); Glennis O. Boatwright and Donald W. Goss (Bushland, TX, now with SCS, Lincoln, NE); Sherwood B. Idso, Paul J. Pinter, and Robert J. Reginato (Phoenix, AZ); Betty L. Klepper, Robert E. Ramig, and Ronald W. Rickman, (Pendleton, OR); Jack A. Morgan (Fort Collins, CO); Jack T. Musick (Bushland, TX); and, Jerry C. Ritchie (Beltsville, MD). Many other scientists and technicians at these different locations also have made valuable contributions. Carl W. Carlson, Assistant Administrator (now retired) was a strong and consistent supporter of this research. Without his help, it would never have started. C. E. Evans (now retired), J. M. Vetterling, J. R. Johnston, R. D. Plowman and C. D. Ranney, Area Directors, also have supported the research objectives.

People from other organizations who have been active participants are Galen F. Hart (Washington, DC), Gregory A. Larsen (Fort Collins, CO now with Hewlett-Packard) and Lyle F. Lautenschlager (Houston, TX), all of the Statistical Reporting Service; Pat Ashburn (now with FAS, Washington, DC), Jim Haynes (now deceased), and John Phillips (McLean, VA, now with FAS, Washington, DC) all with the Central Intelligence Agency; and J. L. Rogers (Houston, TX) with Federal Crop Insurance Corporation representing the Foreign Agricultural Service. The main interest of these groups is forecasting crop production domestically and in foreign countries. Various people from NASA participated from time to time. Henry Nix (Australia) advised on the project, as did James R. Welsh (Colorado State University).

All of the original objectives of the Wheat Yield Group have been accomplished to varying degrees. Four models have been developed for characterizing different aspects of wheat and its environment. All have been published in some form and are described in the following chapters. Two of the models are documented and available for testing; both have been subjected to various sensitivity analyses. A unique aspect of these models is the attempt to characterize mathematically the dif-

ferences among cultivars so that the models will be applicable world-wide. These models may also be used in tropical areas of the world to help interpret yield data from benchmark soils in cooperation with AID and SCS. The first conceptual model for wheat was developed by Dale F. Heermann with help from J. R. Welsh and J. F. Benci (CSU) and A. Klute, E. L. Fiscus, and W. O. Willis (ARS), all of Fort Collins, CO; and D. E. Smika (ARS) and R. W. Shawcroft (ARS, now CSU), Akron, CO. Joe Ritchie, working with Henry Nix and others, developed working models for both wheat (CERES-Wheat) and corn (CERES-Maize). Don Baker, with help from Smika, Black, Bauer, and Willis, developed a physiological process level model called WINTER WHEAT. J. E. Chance and E. W. LeMaster at Pan-American University, working with Craig Wiegand and others at Weslaco, developed a spectral model for light absorption by crop canopies. This spectral model will help provide the linkage between remotely sensed spectral data and the environmental variables that drive the crop models. Also, extensive research by Jackson, Reginato, Pinter and Idso at Phoenix has provided descriptive models to use radiometry for estimating plant canopy temperature and water stress.

Various members of the Wheat Yield Group have assembled and made available a wide variety of unique and valuable data sets for developing and testing models. These include: pertinent literature; research in growth chambers at Duke University; research in controlled climate SPAR (Soil-Plant- Atmosphere Research) units in Mississippi; and field research plots at various locations. Data sets for testing the models have been developed from large commercial fields of winter wheat in Texas (two sites), Oklahoma (one site), Kansas (three sites), Colorado (one site), Nebraska (two sites), Montana (two sites), and Oregon (three sites). Similar data sets for spring wheat (and durum) have been acquired in North Dakota, (six sites, 14 farms) and Montana (two sites). These sites were instrumented to gather climate-related data and plant and soil data at defined phenological growth stages. The total data set from all sites, usually three years for each site, are being compiled into a computerized data base by Lautenschlager. Additional, information on major wheat varieties used in Russia has been assembled through excellent cooperation and seed supplies from Dr. V. E. Johnson, ARS (Lincoln, NE). Performance and yield studies on two Russian winter wheat varieties were conducted by Black at Sidney, MT, during 1976, 1977, and 1978, and on one Russian spring wheat variety by Bauer at Mandan, ND during 1977 through 1982.

Another major contribution of this project was sponsoring the design and construction of several 3-band, hand-held spectral radiometers. These bands correspond to key wave bands (0.63-0.69, 0.76-0.90, and 1.55-1.75 m) of the LANDSAT satellite thematic mapper. The radiometers have been used at several locations for crop assessments and the data obtained from a critical link with satellite data. C. J. Tucker and L. S. Walter (NASA), located at the Goddard Space Center (Greenbelt, MD) were principal cooperators.

An outgrowth of the Wheat Yield Group was the funding of a similar group for developing and testing a physiologically-based soybean model. Using cooperative agreements with Land Grant Universities, two different models have been developed and are being tested -- GLYCIM at Mississippi State, MS and SOYGRO at Gainesville, FL. The SRS has cooperated in these efforts also.

Another cooperator and major funding source for GLYCIM is the CO_2 Project Office of the Department of Energy (DOE). When validated, GLYCIM will be used to assess the effects of the world-wide increase in atmospheric CO_2 levels. A crop modeling effort, largely with ARS and Mississippi State University which preceded the Wheat Yield Group, has produced GOSSYM, a process level simulation model for cotton. The ARS groups working on yield models have contributed to and, to a degree, have been absorbed into the large, multi-agency, AgRISTARS program.

The models CERES-Wheat, CERES-Maize, and GOSSYM are all being tested currently by user groups for operational purposes. While none of the models arising from the Wheat Yield Group are presently being used fully for operational on-farm decisionmaking or crop forecasting, such uses are nearing reality. Much has been learned during the development of the models about the manner in which plants grow and how to characterize growth numerically. We now have more information than before about the effects of environment on growth and how to express those effects mathematically. Some of this information already is being used by FAS and CIA in various ways to help forecast foreign crop yields. These models and the data bases developed by the ARS Wheat Yield Group provide a firm scientific foundation for future research on modeling per se, plant growth and development, environmental stresses and their effects, and yield forecasting. Just as this research was based on past efforts, so will future efforts be based on this one. One expectation from this project is improved integration and use of climatic and remotely acquired data for evaluating environmental changes such as rising CO_2 levels and making crop forecasts and on-farm management decisions of various kinds. Another expected result is that crop models will help in the development and optimization of improved farming systems for the different physiographic regions. There is tremendous potential for application of the results from this exceptional research effort to national and world-wide problems.

In different ways this project provided focus and mission for the group involved, and illustrates the diversity of expertise needed for such an undertaking. In effect, the research has been directed toward describing a biological system. This effort has impacted science and will continue to have impact through articles and reports as they are published, and as the participants may alter their perspectives based on the results.

There is no substitute for good cooperation to do good research. Thus, this document is dedicated to our erstwhile colleague, Dr. W. A. Raney, and to the spirit of cooperation he encouraged during his career in ARS.

ACKNOWLEDGMENT

The authors acknowledge the exceptional help of Sharon L. Skaluba in the typing and preparation of this document.

245

CHAPTER 2. DESCRIPTION OF DATA COLLECTION SITES AND METHODS.

A. NORTHERN GREAT PLAINS: WINTER WHEAT

J. K. Aase and A. L. Black[1]

Two winter wheat (Triticum aestivum L.) fields each in 1980 and 1981 were selected for the study. The fields were all in semiarid northeastern Montana on medium-textured soils developed on glacial till. The fields were made available by cooperating farmers who performed all seedbed preparation, seeding, fertilization, pest control, and harvesting.

I. LOCATION INFORMATION

Detailed descriptions of the fields are listed in Table 1. The Daniels and Zoanni sites were relocation fields selected in the spring of 1980 because the wheat fields originally selected in the fall of 1979 had poor stands in the spring of 1980 and were deemed not to be representative of a uniform winter wheat stand. The 1980 wheat yields were low because of drought. The climate data shown in Table 2 are considered representative of the general climate for all fields under consideration.

Each field was instrumented as described in Chapter 3. The remote data acquisition system was placed in a small fiberglass shelter located near the field boundary, convenient to the access road. The instrumentation was placed in the field 30 to 60 m from the shelter except for the electronic rain gauge which was located along the field boundary. A small plastic rain gauge was attached to a convenient fence post. The data, except from the plastic rain gauge, were recorded every half hour on cassette tape. Data were transferred to the station computer for filing and editing. The files were later put on 1600 BPI 9-track magnetic tape and sent to Houston, Texas for further processing. (See Chapters 4 and 7).

II. MANAGEMENT INFORMATION

Pertinent field and operational management details are listed in Table 3.

III. SOILS

Soil maps for each field are reproduced in Figures 1 through 4. Symbols on the maps are explained in the accompanying Legend. (Pedro and Brockman, 1980; Richardson and Hanson, 1977).

Soil water content was determined by neutron attenuation at six locations in the field near the plant sampling strips. Measurements were made at the center of 30-cm depth increments to a depth of 180 cm.

Four or six soil samples, each from the same depths where soil water was measured, were taken one time for bulk density, particle size analysis, and soil water desorption curve determinations. Bulk density was determined from known core volume and oven dry soil mass (Table 4). The hydrometer method was used for particle size determinations. Desorption curves were determined by compositing the samples from each depth and then placing duplicate soil samples on pressure plate soil water extraction apparatus and extracting the water at 0.1-, 0.33-, 1-, 2-, 3-, 8-, and 15-bars pressure (Table 5). Water content at 15-bar

[1] Soil scientists, Agricultural Research Service, U. S. Department of Agriculture, P. O. Box 1109, Sidney, Montana 59270 and P. O. Box 459, Mandan, North Dakota 58554, respectively.

Table 1. Site descriptions for 1980 and 1981 winter wheat sites.

Cooperator	Daniels	Zoanni	Rasmussen	Deubner
Year	1980	1980	1981	1981
State	Montana	Montana	Montana	Montana
County	Richland	Richland	Richland	Sheridan
Township	T25N	T26N	T23N	T31N
Range	R56E	R57E	R58E	R56E
Section	Middle 1/3 36	W NW 33	NW NW 15	NW 32
Latitude	47°52'N	47°58'N	47°45'N	48°24'N
Longitude	104°26'W	104°22'W	104°16'W	104°28'W
Field Size (ha)	83	19	13	45
Elevation (m)	700	700	680	640

pressure was used as an estimate of the lower limit of plant-available water. Based on the 0.33- and 15-bar water content values, data of available water for the sites are listed in Table 6.

IV. AGRONOMIC

Estimates of plant stand count were made in the spring of 1980 on the Daniels and Zoanni sites and in the fall of 1980 and again in the spring of 1981 on the Deubner and Rasmussen sites. Stand counts were obtained at each sampling by counting the number of plants in six randomly selected 1-m row segments.

On a weekly basis in 1980 and on a bi-weekly basis in 1981, dry matter samples were collected from predetermined sample segments in each field. The sample segments consisted of two parallel strips each 4 rows wide. The strips were separated by ca. 15 m. Six plant samples consisting of 4 rows, 1 meter long, were then clipped at the ground surface from each strip for a total of 12 samples for each sampling date. The samples were brought to the laboratory where they were separated into green leaves, stems, and heads and dried at 57°C for dry matter determination. In addition to sampling the 12 sites, 12 additional random samples were taken from each field at harvest, each sample consisting of three rows 2.4 m long.

Grain harvest samples were processed to determine total dry matter and grain yield. From each of the first 12 harvest samples, numbers of heads were

Table 2. Monthly rainfall and temperatures for 1980 and 1981 and long-term averages at the Eastern Agricultural Research Center, Sidney, Montana.

Item	Month												Total or Average
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Precipitation (mm)													
1980	19	7	3	9	7	49	19	74	37	49	12	16	302
1981	1	5	3	28	14	81	65	65	15	19	10	14	321
Long-term avg.	10	10	12	29	52	72	45	42	33	22	11	11	350
Mean Temperature (°C)													
1980	-12	-7	-2	10	16	19	22	18	14	9	2	-7	7
1981	-3	-4	4	10	14	17	22	22	16	8	3	-7	9
Long-term avg.	-13	-8	-2	6	13	17	21	20	14	8	-1	-8	5
Last killing frost in spring*													
1980 - 15 May													
1981 - 11 May													
Long-term avg. - - - - - - - - - - - - - - - - - 16 May													
First killing frost in fall*													
1980 - 11 October													
1981 - 16 September													
Long-term avg. - - - - - - - - - - - - - - - - - 19 September													
Frost free period													
1980 - 148 days													
1981 - 127 days													
Long-term avg. - - - - - - - - - - - - - - - - - 125 days													

*In this summary 0° is considered to be a killing frost.

Table 3. Management information for 1980 and 1981 winter wheat sites.

Cooperator	Daniels	Zoanni	Rasmussen	Deubner
Year	1980	1980	1981	1981
Previous Crop	Fallow	Fallow	Fallow	Fallow
Cultivar	Roughrider	Roughrider	Roughrider	Roughrider
Row spacing (cm)	25	25	25	25
Row orientation	E-W	N-S	E-W	N-S
Seeding rate (kg/ha)	56	60	56	59
Drill type	Hoe	Hoe	Hoe	Hoe
Fertilizer material (N-P-K) (kg/ha)	78(18-46-0)	62(18-46-0)	67(11-48-0)	78(18-46-0)
Seeding date	9/11/79	9/10/79	9/10/80	9/10/80
Harvest date	7/23/80	7/25/80	7/28/81	7/27/81
Farmer yield estimate (kg/ha)	740	940	2490	2560

counted and following threshing numbers of kernels from each sample were counted on an automatic seed counter. Test weight, percent water, and percent protein of the grain were also determined on the first 12 regular harvest samples. Additionally, from the regular sampling sequence, 12 samples each of 20 individual heads were collected for determination of number of kernels per head and kernel weight.

Plant height, number of live tillers, and number of green leaves were determined on 20 randomly selected plants each time dry matter samples were taken. Growth stage determinations according to the Feekes scale (Large, 1954) were made on at least each dry matter sampling date.

V. RADIATION MEASUREMENTS

During 1980, a handheld three-band radiometer was used to measure wheat radiances in the red (0.63 to 0.69 m) and near infrared (0.76 to 0.90 m) wavebands at the Daniels and Zoanni sites. Readings were made as follows: Two dark background readings (no light allowed to enter lenses), four readings from a barium sulfate painted reflectance standard, six readings from the

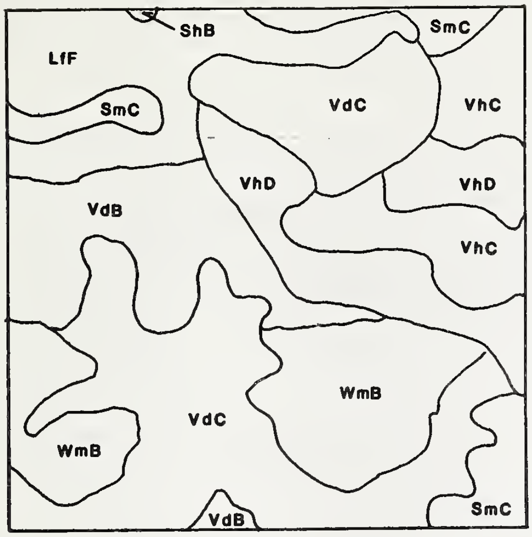

Figure 1. Soil survey of Daniels site located in section 36. Sampling done on VdB (Vida Clay loam, 1 to 4% slope).

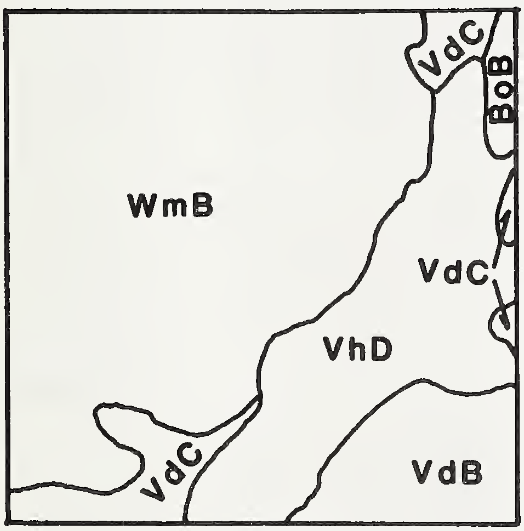

Figure 2. Soil survey of Zoanni site located in section 33. Sampling done on WmB (Williams loam, 0 to 4% slope).

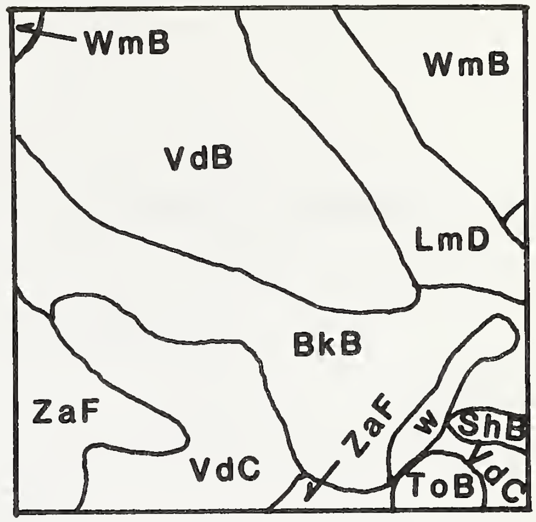

Figure 3. Soil survey of Rasmussen site located in section 15. Sampling done on VdB (Vida Clay loam, 1 to 4% slope).

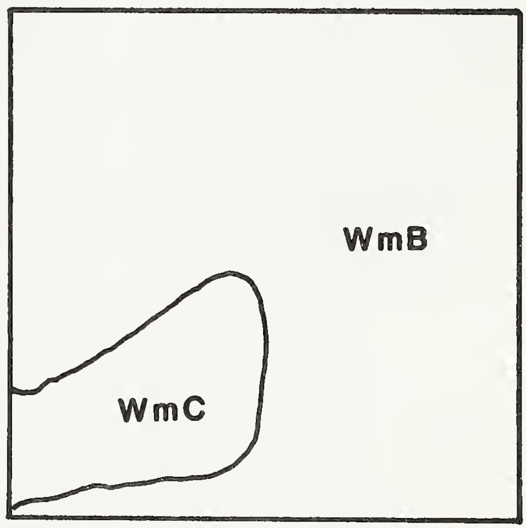

Figure 4. Soil survey of Deubner site located in section 32. Sampling done on WmB (Williams loam, 0 to 4% slope).

Legend associated with field sites only, as shown on Figures 1 through 4 and described in Table 1

Site	Symbol	Soil, slope
Daniels	VdB	Vida clay loam, 1 to 4%
	VdC	Vida clay loam, 4 to 8%
	VhC	Vida-Zahill complex, 4 to 8%
	VhD	Vida-Zahill complex, 8 to 15%
Zoanni	WmB	Williams loam, 0 to 4%
Rasmussen	VdB	Vida clay loam, 1 to 4%
Deubner	WmB	Williams loam, 0 to 4%
	WmC	Williams loam, 4 to 8%

Table 4. Average bulk density at six soil depths*

Cooperator	Soil depth (cm)†					
	15	45	75	105	135	165
	gcm^{-3}					
Daniels	1.40	1.52	1.63	1.68	1.63	1.66
Zoanni	1.40	1.33	1.48	1.62	1.62	--
Rasmussen	1.48	1.43	1.65	1.71	1.73	1.72
Deubner	1.57	1.44	1.55	1.52	1.66	1.72

*Average of six samples.

†A 15-cm soil sample centered at stated depths.

Table 5. Water desorption values as determined on pressure plate apparatus.

		Soil depth (cm)†					
Cooperator	Pressure	15	45	75	105	135	165
	Bars	% H_2O by weight					
Daniels	0.10	38.40	35.46	35.06	38.32	38.96	39.84
	0.33	26.55	25.14	25.44	29.50	31.15	31.33
	1.00	21.03	19.48	18.27	21.29	22.75	23.41
	2.00	18.13	16.77	15.64	18.25	18.93	19.44
	3.00	16.68	15.27	14.11	16.44	16.51	17.57
	8.00	13.53	12.20	11.49	13.06	13.03	14.24
	15.00	12.21	10.87	10.48	11.77	11.63	13.00
Zoanni	0.10	36.19	35.96	36.82	36.36	35.89	34.24
	0.33	24.33	26.20	28.57	28.78	28.27	25.57
	1.00	17.87	19.26	20.73	21.04	20.40	18.04
	2.00	14.86	16.22	16.69	17.18	16.70	14.16
	3.00	13.77	15.00	15.38	15.78	15.46	13.41
	8.00	10.89	11.48	11.85	12.06	12.06	10.44
	15.00	9.87	10.61	10.76	11.06	11.17	9.27
Rasmussen	0.10	31.61	27.67	31.81	35.21	36.37	34.10
	0.33	20.09	18.96	22.22	26.46	27.79	26.48
	1.00	15.46	14.34	17.39	19.79	20.65	19.99
	2.00	13.41	12.39	15.09	17.07	17.69	17.16
	3.00	11.99	11.29	13.79	15.59	15.91	15.54
	8.00	9.63	9.13	11.03	12.48	12.72	12.20
	15.00	8.98	8.31	10.08	11.41	11.58	11.21
Deubner	0.10	30.79	32.38	31.90	30.55	32.35	31.58
	0.33	20.19	22.79	23.17	22.10	23.36	24.13
	1.00	14.92	17.34	16.48	16.06	16.67	16.75
	2.00	12.70	15.08	14.22	13.34	13.68	14.60
	3.00	11.48	13.64	12.70	11.86	12.32	12.88
	8.00	9.36	10.70	10.05	9.68	9.82	10.61
	15.00	8.93	9.92	9.71	9.01	9.68	10.10

†A 15-cm soil sample centered at stated depths.

Table 6. Available water-holding capacity by depth based on 0.33- and 15-bar pressure plate values.

Cooperator and Soil Type	Soil depth (cm)* 15	45	75	105	135	165
	- - - - - -	- - - -	- - - cm	- - -	- - - -	- - - - - -
Daniels - Vida clay loam	6.0	6.5	7.3	8.9	9.6	9.1
Zoanni - Williams loam	6.1	6.2	7.9	8.6	8.3	---
Rasmussen - Vida clay loam	4.9	4.6	6.0	7.7	8.4	7.9
Deubner - Williams loam	5.3	5.6	6.3	6.0	6.8	7.2

* Indicated depth is center of measurement of ca. 30-cm diameter zone of influence.

crop, four standards, two dark. Reflectances were calculated as the ratio of plot radiance to radiance from the barium sulfate standard. Eleven reflectance determinations were obtained during the season from the Daniels site and 12 from the Zoanni site.

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CHAPTER 2. DESCRIPTION OF DATA COLLECTION SITES AND METHODS.

B. CENTRAL GREAT PLAINS: WINTER WHEAT

D. E. Smika[1]

To evaluate the influence of environment on winter wheat growth and development throughout the Central Great Plains, seven field sites were selected. Site identification was by number, the town they were near, County, elevation, longitude and latitude, and section, township, and range (Table 1). Hereafter reference will be by number only. Acreage in wheat each year for the locations in the order of one through seven was 80, 80, 80, 89, 160, 80, and 67, respectively. At sites 4 and 7 continuous winter wheat was grown while at the other five sites a winter wheat-fallow rotation was practiced. Locations 1, 2, 3, and 6 were longer east and west than north and south while locations 4, 5, and 7 were longer north and south than east and west, but all were seeded in a round-and-round fashion from the outside to the inside of each field. Rows were 12 inches apart at locations 1, 2, 3, 5, and 6, and 7 inches apart at locations 4 and 7. Average seeding and harvest dates in numerical sequence was 9-9 and 7-5; 9-11 and 7-1; 9-18 and 6-28; 9-28 and 6-18; 9-6 and 7-17; 9-18 and 7-7; and 10-1 and 7-16, respectively. Seeding rate for the locations in numeral sequence was 30, 20, 30, 60, 60, 45, and 60 lbs/ac, respectively. The variety Centurk was grown at locations 1, 3, and 6, Larned was grown at location 2, Tam 101 was grown at location 4, and Scout 66 was grown at locations 5 and 7. No fertilizer was used at locations 2 and 5, nitrogen fertilizer at the rate of 40 lbs/ac was used at location 1, at 60 lbs/ac at locations 3 and 6, and 90 lbs/ac at locations 4 and 7. Each location was instrumented as described in Chapter 3.

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SOILS

The soils and soil characteristics are described in Table 2. A soils classification map of each location is presented in Figure 1. Soil water was determined gravimetrically from 12 sites within each field location. Samples were collected in 30-cm increments to a depth of 180 cm at seeding, in late fall, in early spring following growth initiation, at heading, and at maturity. Each site was permanently located such that resampling would occur in the same general area. All plant sampling at each location occurred at the same site as the soil water sampling sites. Samples for NO_3-N were collected at each time soil water was determined.

AGRONOMIC

Plant stands were determined each fall between 7 to 14 days after seeding. Two adjacent rows of sufficient row length at each site were counted so that each subsequent sampling for tiller counts, head number and dry weight determinations could be made from known initial stand densities. The frequency of sampling varied from location-to-location, and between years at some of the locations. Sample size was 2 rows 2 meters long in the fall, and 2 rows 1 meter long at all subsequent samplings except at maturity when 2 rows 3 meters long was harvested. Also, at maturity 10 heads were randomly selected form the plant canopy at each site at each location. Each head was separately hand threshed, kernels counted, and weighed. Growth stage was

Table 1. Identification of seven locations in the Central Great Plains.

Number	City name	County name	Elevation Ft.	Longitude	Latitude	Section	Township	Range
1	Akron, CO	Washington	4500	102°59'16"	40°09'55"	SW 5	2N	50W
2	Tribune, KS	Greeley	3625	101°47'04"	38°27'09"	SW 30	18S	40W
3	Garden City, KS	Finney	2925	100°46'07"	38°09'09"	SW 7	22S	31W
4	Medford, OK	Grant	1235	97°40'19"	36°52'41"	NW 29	28S	4W
5	Albin, WY	Banner (Nebr)	4800	103°59'43"	41°27'48"	N 10	17N	58W
6	Paxton, NE	Keith	3240	101°24'52"	41°01'48"	SE 11	12N	36W
7	Mankato, KS	Jewel	1780	98°15'00"	39°49'25"	NE 7	3S	6W

Number	City name	Average Frost-free days	Average date of last killing frost in the spring	Average date of first killing frost in the fall	Length of record
1	Akron, CO	149	May 6	October 3	74 years
2	Tribune, KS	158	May 2	October 8	71 years
3	Garden City, KS	167	April 28	October 13	74 years
4	Medford, OK	long-term weather records not available			
5	Albin, WY	long-term weather records not available			
6	Paxton, NE	long-term weather records not available			
7	Mankato, KS	long-term weather records not available			

Table 2. Soil and soil characteristics at seven field sites in the Central Great Plains.

Site	Soil type	Avail. water in 180 cm profile	Organic matter	pH
		cm	%	
1	Platner sandy loam	33.8	1.2	7.4
2	Richfield silt loam	32.8	0.9	7.6
3	Ulysses silt loam	29.3	1.1	7.6
4	Renfrow silt loam	55.0	2.4	6.6
5	Rosebud loam	30.2	1.0	7.9
6	Daws very fine sandy loam	29.0	0.8	7.2
7	Harney silt loam	29.2	2.0	6.9

determined according to the Feekes scale (1) at each sampling. From the maturity samples, grain yield, straw yield, test weight, and protein content was determined.

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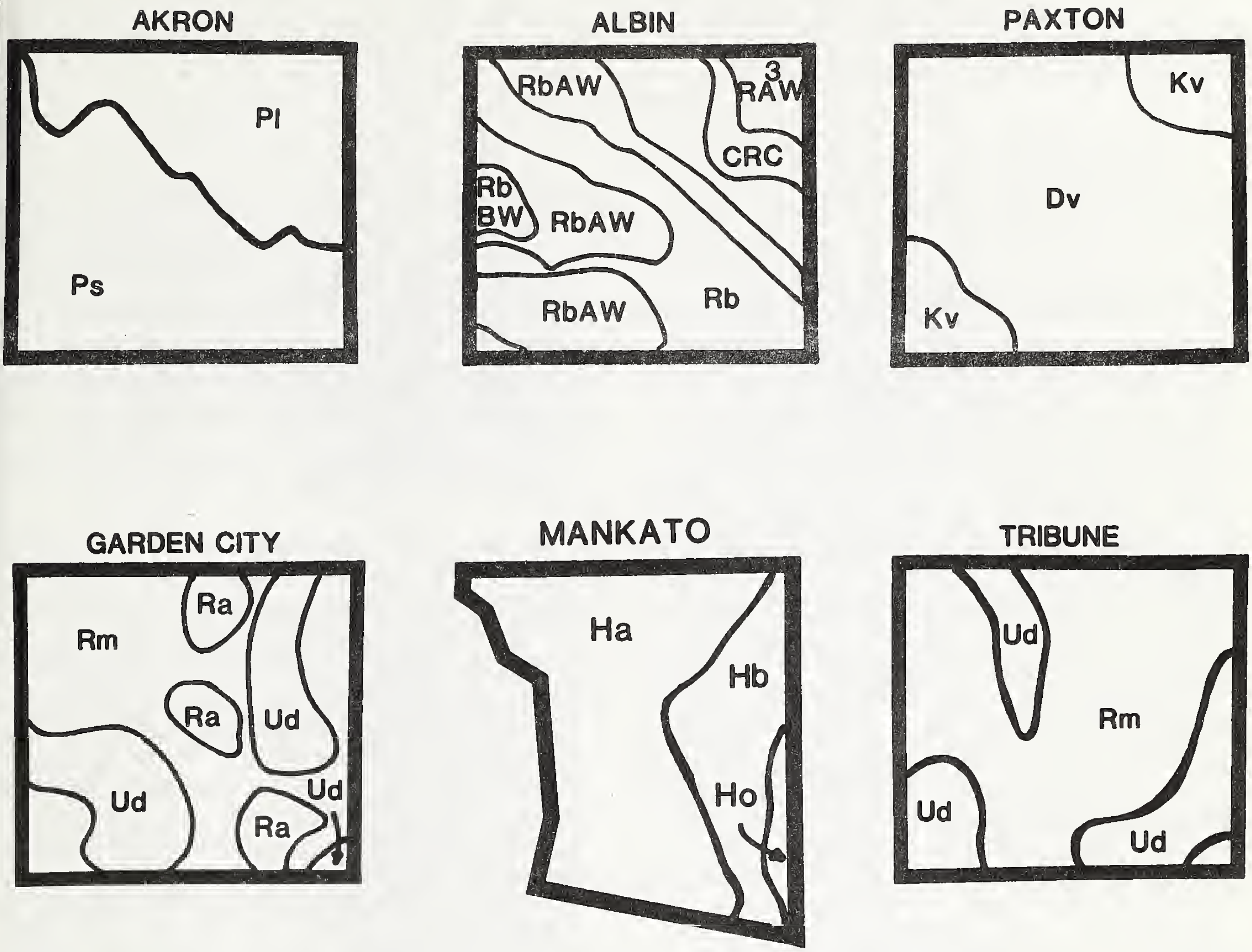

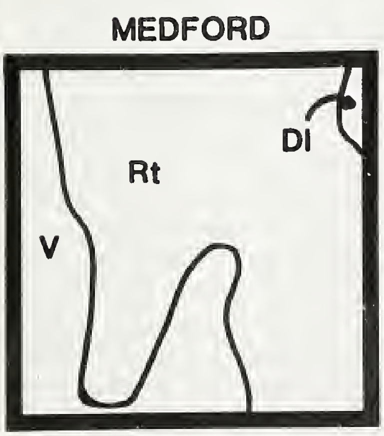

CRC	Canyon-Rosebud loam
D1	Oswego silt loam
Dv	Daws very fine sandy loam
Ha	Harney silt loam 0-1% slopes
Hb	Harney silt loam 1-3% slopes
Ho	Holdredge silt loam
Kv	Keith very fine sandy loam
P1	Platner loam
Ps	Platner sandy loam
Ra	Randall clay
Rb	Rosebud loam 0-1% slopes
RbAW	Rosebud loam 1-3% slopes
RbBW	Rosebud loam 3-5% slopes
Rm	Richfield silt loam
Rt	Ranfrow silt loam
3RAW	Rosebud loam mod. deep 1-3% slope
Ud	Ulysses silt loam 1-3% slopes
V	Vernon clay loam eroded phase

Figure 1. Soil classification for each of the seven field locations.

245

CHAPTER 2. DESCRIPTION OF DATA COLLECTION SITES AND METHODS.

C. SOUTHERN GREAT PLAINS: WINTER WHEAT

J. T. Musick and D. A. Dusek[1]

LOCATION

Two sites were selected to represent the winter wheat production regions of the Southern Great Plains. One site was located at the USDA Conservation and Production Research Laboratory, Bushland, Randall Co., Texas. The 12-ha site is representative of the Southern High Plains land resource area that includes the Texas and Oklahoma Panhandles and a small part of eastern New Mexico and southwest Kansas. The coordinates are 35° 10' 02" N latitude and 102° 05' 08" W longitude. It is located in the Soil Survey of Randall Co., Texas, sheet No. 1, as the NW quadrant of the SW one-fourth of Section 198 (Jacquot et al. 1970)[2]. The soil is classified as Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls), a major soil series of the area. Elevation is about 1145 m.

Pullman soils have been described by Taylor et al. (1970) and by Unger and Pringle (1981). Based on the determined lower limit of soil water availability to plants for the site, the profile contained 209 mm of water to 1.2-m depth and 339 mm to the 1.8-m depth. At the -15 bar potential, the profile to the two depths contained 273 and 403 mm of water, respectively. Winter wheat has the ability to deplete soil water below the -15 bar value (Musick et al. 1976). Plant available water stored in the -13 to -15 bar range is 156 and 231 mm to 1.2- and 1.8-m depths, respectively (Unger 1970). Bulk densities are in the range of 1.25 to 1.40 Mg/m^3 for the Ap horizon (tillage zone) and 1.5 to 1.65 for the subsoil Bt horizons to 1.8 m.

A second site was selected in the Rolling Red Plains land resource area approximately 8 km southeast of Vernon, Wilbarger Co., Texas. This site, located near the Texas-Oklahoma state line, is representative of a major wheat production area that runs north and south from southwest Oklahoma into north-central Texas. This site has the warmest temperatures and the shortest growing season of the data collection sites for the wheat yield model project. The test during the first two seasons was located on a 47-ha field (Joe Lowe farm). The third season test was located on an adjacent 41-ha field (Dean Byers farm) because the Lowe field was not seeded to wheat the third year. Coordinates for the Lowe field are 34° 07' 45" N latitude and 99° 11' 44" W longitude. The fields are located on page 30 of the Soil Survey, Wilbarger Co., Texas (Koos et al. 1959). The Lowe field is the eastern one-half of section 44 and the Byers field is the northwest quarter of section 43. Elevation is about 365 m.

Soils in both fields near Vernon were classified in the original county soil survey as Abilene clay loam (fine, mixed, thermic Pachic Paleustolls). This soil series in Wilbarger Co., was later reclassified as Rotan clay loam and both fields have this present classification.

At the lower limit, the soil water con-

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[2] The year, when it follows the author's name, refers to Literature Cited.

tent determined to a 1.2-m depth was 216 mm for the Lowe field and 219 mm (or the Byers field. At the -15 bar potential, water content for the 1.2-m profile was determined by SCS laboratory tests as 283 mm, and the plant available range of -13 to -15 bar was 131 mm. Bulk densities were 1.4 Mg/m^3 for the Ap horizon and 1.5 to 1.7 for the Bt horizons to 1.2-m depth.

CLIMATE

Long-term average precipitation and maximum and minimum air temperatures are given by months in Table 1. Also given are average last spring and first fall freeze dates. Annual precipitation averages 464 mm at Bushland and 652 mm at Vernon. At both locations, seasonal precipitation from normal seeding dates (early to mid-October) to maturity (near late May at Vernon and mid-June at Bushland) averages approximately one-half the annual amount. The warmer air temperatures at Vernon cause the frost-free mean growing season to average 221 days compared with 187 days at Bushland.

Average monthly precipitation and air temperature data taken at the sites during the three seasons from start to termination of the data acquisition system operation are presented in Table 2. Total precipitation was near normal during the 1979 and 1980 growing seasons at both locations while the 1981 season was drier than normal. Maturity was delayed in 1980 because of a cool spring.

FIELD MANAGEMENT

Continuous annual cropping is the predominant practice for wheat production in the Rolling Red Plains while both continuous cropping and cropping after summer fallow are practiced in the drier Southern High Plains.

Bushland: The 12-ha field was managed by laboratory staff. The first wheat crop planted in 1978 followed continuous dryland wheat on the west half of the field. The east half had a fallow strip next to the wheat and a dryland grain sorghum strip on the east side. The sorghum was harvested 11 Sept., and then the strip was tilled and irrigated. The irrigation recharged the soil profile to nearly the same water content as the fallow strip. A 141-mm rain on 20-21 Sept. recharged the soil water on the continuous wheat strip. However, some surface runoff from the upper part of this area (represented by sites 1, 2, 5, and 6) resulted in reduced water storage and lower yields (Table 5). The surface runoff was largely retained by a dike on the lower section of the field. Sites 7, 8, 11, and 12 representing the lower section had soil water at planting and grain yields to largely similar to those on the fallow area (sites 3, 4, 5, and 6).

The field was in annual cropping for the 3-year test. Since planting continuous dryland wheat would have created a risk of crop failure because of dry soil profile conditions after the 1979 and 1980 harvests, the field was irrigated prior to seeding in the fall. Irrigation application of about 150 mm wet the dry soil profiles to the 0.6 to 0.9-m depth. Irrigation plus some summer rain produced soil water contents at seeding that were similar to those normally attained after summer fallow. Average soil water data for the field are presented by dates and depths in Table 3.

Variety TAM W-101 was seeded at the rate of 50 kg/ha on 7 Oct. 1978, 10 Oct. 1979, and 1 Oct. 1980 and harvested on 22 June 1979, 30 June 1980,

Table 1. Average precipitation, air temperatures, spring and fall freeze dates, and mean growing season, Bushland (44 years) and Vernon (30 years). Vernon data are from The National Weather Service.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total or Average
Precipitation -- mm													
Bushland	11	13	19	27	69	74	65	70	44	41	18	13	464
Vernon	24	32	36	61	119	82	54	41	69	77	30	27	652
Air temperature -- °C													
Bushland													
Max.	9.8	12.2	16.7	21.9	26.1	30.9	32.7	31.7	28.2	22.9	15.6	11.2	21.7
Min.	-6.4	-4.3	1.1	4.3	9.5	14.8	17.3	16.1	12.3	6.1	-1.1	-4.7	5.3
Vernon													
Max.	13.0	15.5	17.6	26.2	30.2	34.7	37.2	37.2	36.0	28.6	19.7	14.0	25.7
Min.	-1.5	1.1	4.4	10.6	15.4	20.4	22.6	21.9	17.7	11.4	2.7	.2	10.6
Avg. freeze dates -- °C				Spring		Fall		Mean growing season -- days					
Bushland				20 Apr.		24 Oct.				187			
Vernon				31 Mar.		7 Nov.				221			

Table 2. Precipitation totals and average max. and min. air temperatures by months from start of data collection after seeding until it was stopped at maturity, Bushland and Vernon, TX. The max. and min. are clock hour integrated values.

	Crop Season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Precipitation -- mm										
Bushland	1979	4	48	1	19	2	11	16	46	57
	1980	33	8	4	15	7	43	35	60	28
	1981	2	5	5	2	3	41	10	54	
Vernon	1979	13	39	-	50	2	51	41	113	
	1980		49	41	8	7	8	2	150	
	1981	12	17	38	2	20	49	71	19	
Avg. air temperature -- °C										
Bushland										
1979	max.	20.5	11.9	4.7	1.1	12.1	13.8	19.2	23.6	28.0
	min.	6.6	2.2	-6.9	-10.0	-3.6	-0.8	4.3	8.8	12.7
1980	max.	21.8	10.7	10.8	7.9	8.8	13.6	17.9	21.9	33.7
	min.	5.6	-1.8	-4.9	-5.6	-2.1	-3.0	1.8	8.2	16.2
1981	max.	16.1	11.2	12.0	10.1	13.1	13.8	23.1	24.2	
	min.	-.1	-2.2	-3.4	-5.2	-4.6	0.6	6.6	9.0	
Vernon										
1979	max.	27.7	16.9	11.2	3.5	11.2	17.9	22.0	27.2	
	min.	8.5	5.4	-3.6	-5.6	-0.2	4.8	8.3	13.0	
1980	max.		14.9	12.2	8.9	12.6	17.3	23.4	27.8	
	min.		2.1	0.1	-0.9	-2.2	1.9	7.0	18.4	
1981	max.	18.4	16.6	13.6	11.2	14.7	17.7	25.7	26.1	
	min.	3.5	3.9	0.6	-1.9	0.2	5.7	12.5	12.7	

Table 3. Average soil water contents at Bushland for the 12 sites, mm per 0.3-m depth increment and profile totals to 1.2 and 1.8 m.

Depth increment							
1978-79		Oct. 20	Dec. 12	Feb. 27	Apr. 23	July 13	
	1	91	88	87	60	59	
	2	98	94	92	70	53	
	3	91	84	84	68	49	
	4	86	79	78	68	53	
	5	82				64	
	6	80				66	
Total	1.2 m	366	345	341	266	214	
	1.8 m	528				344	
1979-80		Oct. 19	Dec. 18	Mar. 24	Apr. 21	May 30	July 11
	1	77	94	92	82	61	53
	2	89	101	99	96	72	60
	3	84	91	91	87	68	59
	4	72	80	76	76	69	71
	5	69	75				71
	6	76	76				68
Total	1.2 m	322	366	358	341	270	243
	1.8 m	467	517				382
1980-81		Oct. 30	Jan. 7	Mar. 18	Apr. 20	June 18	
	1	100	85	83	59	67	
	2	97	88	78	65	56	
	3	82	72	70	60	52	
	4	70	66	67	66	56	
	5	71	67	71	74	64	
	6	74	71	73	76	67	
Total	1.2 m	338	311	298	250	231	
	1.8 m	483	449	442	400	362	

and 4 June 1981. Row spacing was 25 cm for the 1979 and 1981 crops and 33 cm for the 1980 crop. Row direction was N-S for the first two crops. For the third crop, the north half was seeded N-S and the south half, E-W. Analysis of soil cores to a 1.2-m depth at seeding indicated NO_3-N in the range of 180 to 210 kg/ha, an amount in excess of dryland crop needs.

Vernon: All field operations were performed by the farmer. The first wheat crop was seeded in 1978 following wheat grown for grazing by cattle (Nov. to May) and the second and third crops followed wheat harvested for grain the previous spring. Variety TAM W-101 was seeded at the rate of 67 kg/ha in a "round-the-field" direction. Seeding dates were 6 Oct. 1978, 23-24 Oct. 1979, and 3 Oct. 1980. Harvest dates were 4 June 1979, 12 June 1980, and 21 May 1981. Chemical analysis of soil cores taken after seeding indicated NO_3-N to a 1.2-m depth averaged 115, 160, and 270 kg/ha for the three crop seasons, respectively. A cold weather-related phosphorus deficiency was noted during the winter of 1980-81 that disappeared during spring growth.

DATA COLLECTION PROCEDURES

Each field was instrumented for automated data collection as described in Chapter 3. A standard 20-cm rain gauge was located along with the recording rain gauge. During the first season at both locations, the 12 sampling sites were selected as 3 rows of sites to represent the field as divided into 12 sections. During the next two seasons, the field was sampled as two rows of 6 sites with successive sites located in an alternating pattern across the field. The data acquisition system was centrally located in an insulated shelter. Data were recorded on a clock-hour basis on cassette tape and transferred to the laboratory computer for editing and filing on floppy disks. Floppy disks were used for data transfer to Fort Collins, Colo., and hard copies were sent to Houston, Tex., for data entry by the Statistical Reporting Service to the Martin- Marietta computer. Data summaries were sent to Temple, Tex., and to Manhattan, Kans., for use in testing wheat models.

The data acquisition systems were not available when the study began. They were placed in the field at Bushland before spring greenup (16 Feb. 1979), and at Vernon about 2 weeks after spring greenup (25 Feb.). Prior data, using LI-COR LI-550[3] printing integrators, were taken from seeding as integrated clock-hour air temperature above the crop, soil temperature at the 3-cm depth, and incoming solar radiation. Precipitation was measured using a standard 20-cm rain gauge. At Bushland, climatic data collection started on 8 Oct. 1978, 12 Oct. 1979, and 19 Oct. 1980, and was terminated on 21 June 1979, 29 June 1980, and 4 June 1981, for the three seasons, respectively. Corresponding dates at Vernon were 7 Oct. 1978, 31 Oct. 1979, and 24 Oct. 1980, and 28 May 1979, 8 June 1980, and 16 May 1981, respectively. Both field sites were serviced by the same laboratory staff.

Soil water was sampled gravimetrically by 0.3-m increments to 1.2- or 1.8-m depths at the 12 sites per field after seeding, periodically during the season, and after harvest (Tables 3 and 4). Wet soil conditions prevented

[3] Mention of a trade name or product does not constitute a recommendation or endorsement for use by the U.S. Department of Agriculture.

Table 4. Average soil water contents at the Vernon fields for the 12 sites, mm per 0.3-m depth increment and profile total to 1.2 m.

Depth increment									
1978-79		Oct. 6	Dec. 19	Feb. 23	Mar. 31				
	1	59	58	80	64				
	2	48	58	65	61				
	3	55	65	69	63				
	4	58	65	67	64				
Total	1.2 m	220	246	281	252				
1979-80		Oct. 30	Dec. 10	Mar. 4	Apr. 2	Apr. 29	June 12		
	1	77	82	87	75	56	94		
	2	80	86	88	81	61	81		
	3	82	84	87	87	67	67		
	4	81	83	79	83	69	64		
Total	1.2 m	320	335	341	326	253	305		
1980-81		Nov. 4	Dec. 1	Jan. 5	Feb. 5	Mar. 5	Mar. 30	Apr. 28	May 20
	1	61	88	73	56	60	55	56	42
	2	73	97	87	77	67	64	56	52
	3	79	107	67	88	76	76	69	62
	4	69	97	82	75	70	70	65	62
Total	1.2 m	282	389	309	296	273	265	246	218

gravimetric soil sampling after harvest at the Vernon field in 1979.

During the 1979 season, plant samples were taken from 1-m row lengths from two adjacent rows at the 12 sites. The 1-m row samples were processed separately. The data collected were (1) plants per 1-m row until they became too difficult to separate, (2) initiated tillers at ground level, (3) head number, (4) dry biomass, and (5) plant height. For final harvest, five samples, two 1-m rows per sample, were taken at each site for dry matter, grain yield and yield components. Plant data were taken at Vernon on 8, 13, and 14 dates and at Bushland on 10, 13, and 14 dates for the three seasons, respectively.

In the 1980 and 1981 seasons, the plant area sampled at each site was increased to 1-m^2 (3 or 4 adjacent 1-m rows depending on row spacing). Plants or tillers were sampled for leaf area using an electronic meter and Feekes scale growth stage was determined. Harvest yield was determined from four 1-m^2 sample areas per site. A 1-m^2 additional sample per site was taken as 1-m length rows that were processed separately as individual row-samples for evaluating yield variability. Fifty consecutive heads per site were harvested and processed for yield component data. Average field combine yields were obtained for the three crops at Bushland, and for the two crops on the Lowe field at Vernon, Table 5.

Table 5. Grain yields, Bushland and Vernon, TX, 1979-81.

		Bushland			Vernon		
		1979	1980	1981	1979	1980	1981
		- - - kg/ha - - -			- - - kg/ha - - -		
Site	1	1393	2300	1195	1350	1289	1438
	2	1822	2804	1002	1356	632	1215
	3	3132	2994	1063	2461	1459	1261
	4	2808	2834	826	2462	1695	751
	5	1141	2595	717	2384	1254	1099
	6	1309	2553	920	1779	1321	661
	7	2331	2548	884	1348	1565	1023
	8	3969	2692	896	1743	1768	1206
	9	3595	3178	1054	1821	1999	576
	10	2939	2669	789	2488	1985	854
	11	2464	2860	1003	2005	2213	745
	12	2838	3183	937	1989	2190	1076
Avg.		2478	2767	941	1932	1614	992
Field combine		2419	2790	1068	1875	1690	

Spectral reflectance data were collected on the dates that plant samples were taken during the spring of 1980, using a Mark II Biometer[4] and during the 1981 season. The 3-band radiometer was hand-held at about 1.5 m above ground level over the wheat. Three or 4 radiometer readings were taken over a reflectance standard (barium sulfate pressed powder surface). One reading was taken with a blackout plate (no light) and six readings were taken over the crop at each site. Data were taken over wet and dry soil to be utilized in separating vegetation reflectance from soil background, using the same procedure. Reflectance was calculated as the ratio of radiance over a site in a nadir direction to radiance over the standard.

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245

CHAPTER 2. DESCRIPTION OF DATA COLLECTION SITES AND METHODS.
D. PACIFIC NORTHWEST: WINTER WHEAT

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Information and data on common soft white winter wheat were collected from ten farm fields over the 4-year period, 1979-1982. The fields in north central Oregon were all in the mid-latitude, semiarid climate of Trewartha 1954 (11). The climate of the area is classified in the modified Koeppen system [Critchfield 1966 (2)] as Dsb where D means the average temperature of the warmest month is greater than 10°C and of coldest month 0°C or below; s means the precipitation in the driest month of summer half of year is less than 40 mm and less than 0.33 the amount of the wettest winter month; and b means average temperature of each of four warmest months 10°C or above; temperature of warmest month below 22°C.

The soils at all locations were medium textured silt loams developed from wind blown loess with some admixture of volcanic ash. The farmer cooperator performed all field operations in seedbed preparation, fertilization, seeding, pest control and harvesting.

I. LOCATION INFORMATION

The field locations by cooperator, year, geographic area, United States rectangular survey system, geographical coordinates with estimated elevation and field area are presented in Table 1. Average monthly air temperature and precipitation from nearby weather stations, number of frost-free days with dates of last spring and first fall freezes and geographic coordinates of weather stations are provided in Table 2.

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II. MANAGEMENT INFORMATION

Some of the management information for the location is presented in Table 3. Field operations at the Spratling sites were as follows: The wheat stubble land from the previous crop was moldboard plowed in April, spring tooth cultivated about three weeks later, nitrogen and a small amount of sulfur fertilizer injected into the soil in early May, followed by a light spring tooth cultivation. The fallow was rodweeded once in July and again before seeding wheat about October 1. Weeds were controlled with appropriate herbicide sprays the following April and wheat was combine harvested in August.

Field operations at the Burnet sites included disking the previous wheat crop stubble in late March or early April followed by either sweep or chisel cultivation and spring tooth cultivation. Nitrogen fertilizer was injected into the soil in May followed by a spring tooth cultivation. Fallow was rodweeded once or twice during the June-August period as required to control weeds. Wheat was seeded in late September after a light field cultivation to control germinated weeds, mostly downy bromegrass (*Bromus tectorum*). Broadleaf weeds were controlled with appropriate herbicide sprays the following March and the wheat was combine harvested in July.

At the Martin sites, the previous wheat crop stubble was chiseled twice in March, rodweeded in April, combined fertilizer injection-rodweeded in May and rodweeded once more during the June to September period if needed to control newly germinated and emerged weeds. Wheat was seeded about October 1 after the land had been field cultivated or rodweeded to kill weeds, in particular, newly emerged downy bromegrass. Broadleaf weeds were controlled

Table 1. Site location is by cooperator, year, geographic area, United States rectangular survey system, geographical coordinates, with estimates of elevation and field size.

Cooperator	Year	County	Section		Township†	Range†	Latitude	Longitude	Elevation	Field size
									m	ha
Spratling	1980	Umatilla, OR	NE	S16	3N	33E	45° 45'N	118° 41'W	485	89
Burnet	1980	Sherman, OR	N	S7	1N	17E	45° 30'N	120° 44'W	610	125
Martin	1980	Morrow, OR	NW	S18	1N	25E	45° 34'N	119° 45'W	427	418
Spratling	1981	Umatilla, OR	SE	S9	3N	33E	45° 45'N	118° 41'W	485	190
Burnet	1981	Sherman, OR	N	S7	1N	17E	45° 30'N	120° 44'W	610	59
Martin	1981	Morrow, OR	SW	S7	1N	25E	45° 34'N	119° 45'W	427	154
Spratling	1982	Umatilla, OR	NE	S16	3N	33E	45° 45'N	118° 41'W	485	89
Burnet	1982	Sherman, OR	N	S7	1N	17E	45° 30'N	120° 44'W	610	125
Martin	1982	Morrow, OR	NW	S18	1N	25E	45° 34'N	119° 45'W	427	418

† For Oregon, the Willamette Stone (W 122° 44' 33.551" and N 45° 31' 10.831") are the base lines for range and township designations, respectively.

Table 2. Average monthly air temperature and precipitation recorded at NOAA weather station nearest the field sites, number of frost-free days, and date of spring and fall freeze.

Month	Pendleton, OR†		Moro, OR*		Ella, OR	
	C°	mm	C°	mm	C°¶	mm∫
Jan	0	49	-1	42	0	34
Feb	3	38	1	30	4	24
Mar	6	42	5	26	6	20
Apr	10	37	9	15	9	18
May	14	34	13	21	13	18
June	17	33	16	18	16	14
July	21	9	21	5	20	6
Aug	20	11	20	7	19	9
Sept	16	19	16	15	16	12
Oct	10	35	10	24	11	20
Nov	4	48	4	43	5	33
Dec	2	56	1	43	2	40
Total	-	411	-	293	-	248
Frost-free days	128		150		168	
Spring freeze, 0°C	May 20		May 6		Apr 29	
Fall freeze, 0°C	Sep 25		Oct 3		Oct 14	
Latitude	45°43'N		45°29'N		45°21'N	45°37'N
Longitude	118°38'W		120°43'W		119°33'W	119°48'W
Elevation, m	453		570		594	259

† Pendleton Branch Experiment Station, 1929-1983 average.
* Moro Experiment Station, 1910-1983 average.
¶ From NOAA Heppner, OR. 1941-1970 average.
∫ From Charles Doherty, Ella, OR. 1956-1983 average.

Table 3. Management information for each location.

Cooperator	Previous crop†	Cultivar	Row spacing	Row orientation	Drill type	Seeding rate	Fertilization rate	Seeding date	Harvest date	Yield estimate
			cm			kg/ha	kg/ha N-S	- - - day/mo/yr	- - -	kg/ha
Spratling	Fallow	Stephens	25	N-S	Shovel	67	90-0	7 Oct 1978	26 Jul 1979	4035
Spratling	Fallow	Stephens	25	N-S	Shovel	67	84-9	24 Oct 1979	6 Aug 1980	6053
Burnet	Fallow	Stephens	30	N-S	Shovel	78	62-0	28 Sep 1979	11 Aug 1980	3766
Martin	Fallow	McDermid	30	N-S	Shovel	56	26-0	3 Oct 1979	23 Jul 1980	2939
Spratling	Fallow	Stephens	25	N-S	Shovel	67	90-9	27 Sep 1980	10 Aug 1981	6322
Burnet	Fallow	Stephens	30	N-S	Shovel	78	67-0	29 Sep 1980	28 Jul 1981	5045
Martin	Fallow	Stephens	30	N-S	Shovel	62	27-0	27 Sep 1980	10 Jul 1981	3430
Spratling	Fallow	Stephens	25	N-S	Shovel	67	90-9	2 Oct 1981	30 Jul 1982	4843
Burnet	Fallow	Daws	30	N-S	Shovel	78	100-0	16 Oct 1981	5 Aug 1982	4237
Martin	Fallow	Stephens	30	N-S	Shovel	56	34-0	1 Oct 1981	16 Jul 1982	2018

† Fallow on Spratling was moldboard plowed. Fallow on Burnet and Martin was chisel cultivated and stubble mulched.

with 2,4-D herbicide spray the following April and the wheat was combine harvested in late July.

The sequences of field operations are typical for the respective locations and are dependent on the soils, quantity of crop residues and amount and distribution of the precipitation.

III. SOIL INFORMATION

Soil associations for each field are shown in Figures 1 through 3. The soil series descriptions are given in the pertinent soil survey reports (Mayers et al., 1964 (8); Hosler et al., 1983 (6); Harrison et al., 1964 (5)).

Soils were sampled for bulk density in early spring after fall seeding. Soil samples were taken from the center 25 cm of each 30.5 cm depth increment to a depth of 180 cm with a Utah bulk density sampler. Six samples were taken within one soil mapping unit on each cooperator's farm identified as follows:

Spratling - Walla Walla silt loam, deep, 1 to 7 percent slopes (coarse-silty, mixed, mesic Typic Haploxeroll);

Burnet - Walla Walla silt loam, very deep, 3 to 7 percent slopes (coarse-silty, mixed, mesic Typic Haploxeroll); and

Martin - Ritzville silt loam, 7 to 12 percent slopes (coarse-silty, mixed, mesic Calciorthidic Haploxeroll).

The average bulk densities at six soil depths for each of these soil mapping units (cooperators) are presented in Table 4. On each cooperator's farm, the area of each soil mapping unit was large enough that one portion was in crop and the other in fallow each year, with the crop positions reversed the following year.

The 0- to 15-cm depth was sampled at 10 locations on each cooperator's site, composited, and particle size distribution determined by the pipette method. Results are presented in Table 5 with the American Association of State Highway Officials (1) and Unified Soil Classification Systems (12) designations also listed.

Selected laboratory data for the soil mapping unit at the Spratling, Burnet, and Martin sites are presented in Tables 6, 7 and 8, respectively. Additional information can be obtained by referring to the appropriate references.

In most years, soil samples were taken at seeding time by 30.5 cm increments through a depth of 183 cm for determination of nitrate concentration. Data are presented in Table 9. The soil samples for the 1980 crops were taken approximately March 26 at the beginning of spring growth instead of at seeding in the fall. The nitrates were distributed through the upper 122 to 152 cm of the soil profiles by the winter precipitation. Soil samples were taken at seeding time in the fall for the 1981 and 1982 crops. Anhydrous or aqua ammonia injected into the fallow soil the previous June had been converted to nitrate, but was still concentrated in the upper 31 cm of the soil profile because inadequate rain had occurred during summer to move the nitrates deeper in the soil profile. The higher levels of fertility in the Spratling and Burnet sites are also apparent when compared to the Martin sites. Available potassium, soluble and total phosphorus were not determined as these soils are adequately supplied with potassium and phosphorus.

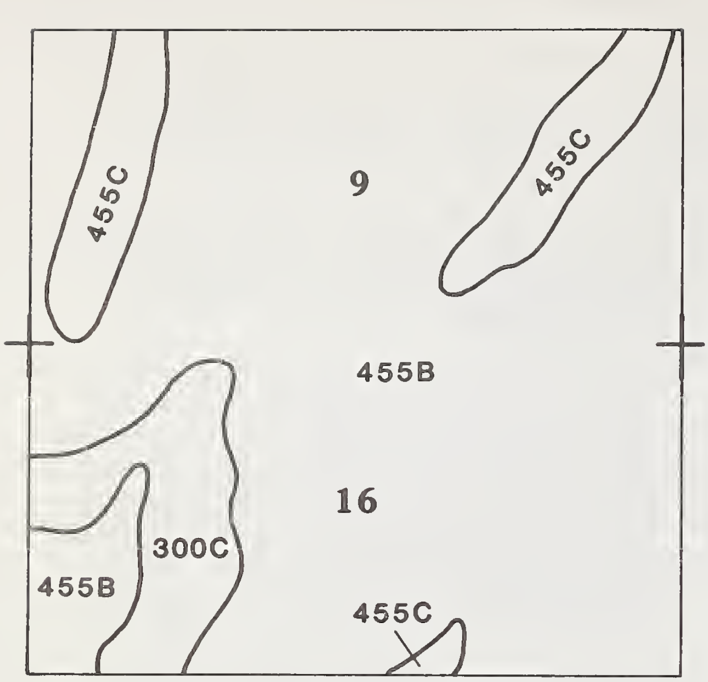

Figure 1. Soil survey map of S 1/2 Section 9 and N 1/2 Section 16, T3N R33E (300C - Anderly silt loam, moderately deep, 7 to 12 percent slopes; 455B - Walla Walla silt loam, deep, 1 to 7 percent slopes; and 455C - Walla Walla Silt loam, deep, 7 to 12 percent slopes). Spratling sites were sampled on either side of the E-W section line in the 455B area (5).

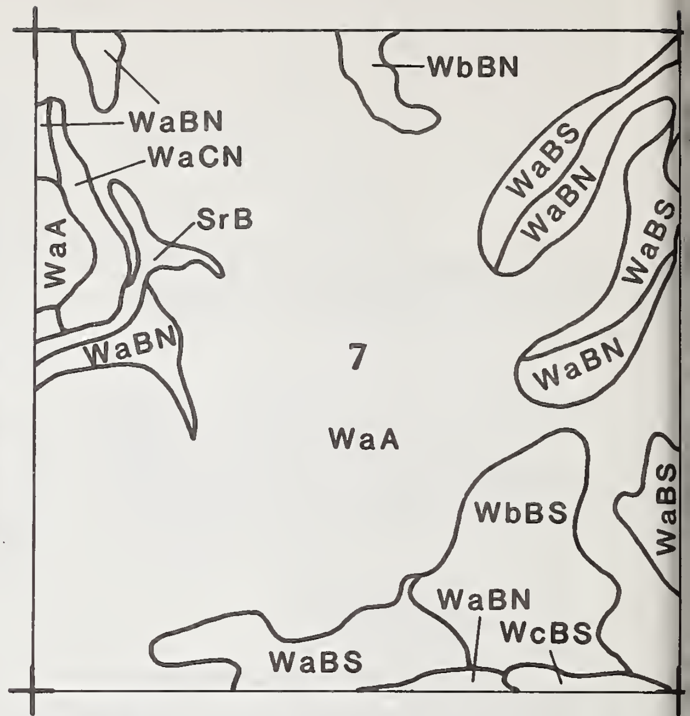

Figure 2. Soil survey map of Section 7, T1S R17E (WaA - Walla Walla silt loam, very deep, 3 to 7 percent slopes; WaBN - Walla Walla silt loam, very deep, 7 to 20 percent north slopes; WaBS - Walla Walla silt loam, very deep, 7 to 20 percent south slopes; WaCN - Walla Walla silt loam, very deep, 20 to 35 percent north slopes; WbBS - Walla Walla silt loam, deep, 7 to 20 percent south slopes; WcBS - Walla Walla silt loam, moderately deep, 7 to 20 percent south slopes; and SrB - Starbuck stony silt loam, 4 to 20 percent slopes). Burnet sites were sampled on either side of the N-S centerline in the WaA area (8).

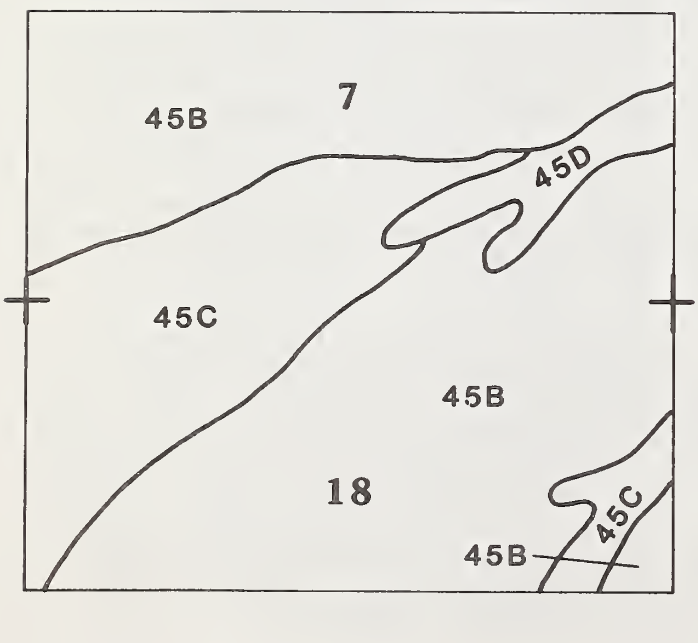

Figure 3. Soil survey map of the S 1/2 Section 7 and the N 1/2 Section 18 T1N R25E (45B - Ritzville silt loam, 2 to 7 percent slopes; 45C - Ritzville silt loam, 7 to 12 percent slopes; and, 45D Ritzville silt loam, 12 to 20 percent slopes). Martin sites were sampled on either side of the E-W section line in the 45C area (6).

Table 4. Average bulk density at six soil depths.†

Soil depth	Cooperator		
cm	Spratling	Burnet	Martin
	g/cm³		
0-31	1.26	1.38	1.28
31-61	1.19	1.31	1.22
61-91	1.23	1.31	1.30
91-122	1.23	1.38	1.30
122-152	1.23	1.38	1.23
152-183	1.23	1.38	1.22

† Average of 6 points or locations.

Table 5. Mechanical analyses of the surface soils on each cooperator's farm.

	Cooperator		
Characteristic	Spratling	Burnet	Martin
Soil series	Walla Walla silt loam	Walla Walla silt loam	Ritzville silt loam
Sand, 2-0.05 mm, %†	13.0	19.0	13.8
Silt, 0.05-0.00 2 mm, %†	68.5	66.6	76.8
Clay, <0.002 mm, %†	18.5	14.4	9.4
AASHO classification (1)	A-4(8)	A-4(7)	A-4
Unified classification (12)	ML-CL	ML	ML

† Analyses by pipette method.

Table 6. Selected laboratory data for a Walla Walla silt loam profile similar to the soil at the Spratling sites near Pendleton, Oregon.[1]

	A1p	A12	B2	C1	C2	C3ca	C4
Depth from Surface (cm)	0-20	20-41	41-66	66-91	91-132	132-183	183-274
pH Sat. Paste	6.7	6.6	6.9	6.9	7.9	8.3	8.2
Organic Carbon (%)	.98	1.03	.61	.52	.41	.27	.12
Nitrogen (%)	-	-	-	-	-	-	-
Cation Exch. Cap. (me/100g)	21.2	20.0	20.6	20.0	20.0	17.5	14.4
Total Sands 2.0-.05mm (%)	17.9	19.0	19.7	20.7	19.7	23.3	22.7
Silt .05-.002mm (%)	66.8	66.3	67.2	67.7	73.1	69.3	66.8
Clay <.002mm (%)	15.3	14.7	13.1	11.6	7.2	7.4	10.5
Bulk Density (gms/cm^3)	-	-	-	-	-	-	-
Moisture held at tensions of:							
0 (%)	-	-	-	-	-	-	-
0.01 (%)	-	-	-	-	-	-	-
0.33 (%)	-	-	-	-	-	-	-
1.5MPa (%)	-	-	-	-	-	-	-
Available water in horizon (mm)	37	37	47	47	75	93	168

[1] USDA Soil Conservation Service Soil Survey Profile S51 Wash-36-2-1 through 7. SW¼SW¼ Sec. 28, T8N,R36E, Walla Walla County, Washington (5,7).

Table 7. Selected laboratory data for a Walla Walla silt loam profile similar to the soil at the Burnet sites near Moro, Oregon.[1]

	Alp	Alpm	A12	B21	B22	C1	C2	C3	C4ca	C5
Depth from Surface (cm)	0-18	18-22	22-43	43-64	64-86	86-127	127-167	167-193	193-269	269-294
ph Sat. Paste	5.9	6.1	6.4	6.7	7.1	7.3	7.4	7.7	7.9	8.0
Organic Carbon (%)	1.25	1.01	.72	.46	.37	.25	.15	.13	.08	.04
Nitrogen (%)	.094	.091	.073	.057	.049	-	-	-	-	-
Cation Exch. Cap. (me/100g)	17.3	17.5	16.9	15.3	14.6	13.8	13.9	12.6	13.7	12.6
Total Sands 2.0-.05mm (%)	29.6	27.3	26.3	24.7	24.9	27.2	33.9	36.9	31.1	30.6
Silt .05-.002mm (%)	58.0	60.3	60.8	63.4	63.8	61.8	57.4	59.2	65.6	65.8
Clay <.002mm (%)	12.4	12.4	12.9	11.9	11.3	11.0	8.7	3.9	3.3	3.6
Bulk Density (gms/cm^3)	1.03	1.19	1.37	1.36	1.39	1.44	1.42	1.33	-	-
Moisture held at tensions of:										
0 (%)	33.4	35.3	36.7	34.4	35.9	32.8	33.6	30.6	33.2	30.9
0.01 (%)	35.2	35.9	36.8	34.1	34.0	33.5	32.5	32.3	33.4	32.0
0.33 (%)	19.6	19.1	22.4	18.1	19.0	18.5	17.7	17.7	16.8	16.3
1.5MPa (%)	6.3	6.6	6.4	6.0	5.7	5.2	5.8	5.7	5.4	4.8
Available water in horizon (mm)	24	6	47	34	42	78	69	41	-	-

[1] USDA Soil Conservation Service Soil Survey Profile S57-Ore-28-5-1 through 10. SE¼SW¼ Sec. 25, T1N, R16E, Sherman County, Oregon (8).

Table 8. Selected laboratory data for a Ritzville silt loam soil similar to the soil at the Martin sites near Ione, Oregon.[1]

	Ap	B21	B22	C1ca	C2	C3	C4	C5
Depth from Surface (cm)	0-23	23-46	46-91	91-109	109-137	137-165	165-198	198-228
pH Sat. Paste	6.2	6.5	7.1	8.2	8.6	9.1	9.0	9.0
Organic Carbon (%)	.77	.64	.47	.35	.42	.28	.24	.25
Nitrogen (%)	.065	.069	.056	.039	.028	.019	-	-
Cation Exch. Cap. (me/100g)	15.2	16.6	13.9	11.6	11.6	13.6	13.6	12.2
Total Sands 2.0-.05mm (%)	17.9	18.4	14.1	14.6	21.9	35.6	25.0	29.2
Silt .05-.002mm (%)	71.7	70.2	76.1	76.9	71.6	58.8	67.9	60.7
Clay <.002mm (%)	10.4	11.4	9.8	8.5	6.5	5.5	7.1	10.1
Bulk Density (gms/cm^3)	1.13	1.2	1.3	1.33	1.29	1.33	1.4	-
Moisture held at tensions of:								
0 (%)	31.7	39.1	40.7	37.4	25.2	33.2	39.3	40.9
0.01 (%)	-	-	-	-	-	-	-	-
0.33 (%)	-	-	-	-	-	-	-	-
1.5MPa (%)	7.1	7.5	6.9	7.2	6.7	7.1	9.0	10.5
Available water in horizon (mm)	-	-	-	-	-	-	-	-

[1] USDA Soil Conservation Service Soil Survey Profile S61 Wash-1-5-1 through 8 (4,7).

Table 9. Nitrate concentration at six soil depths on cooperators sites at seeding time.

YEAR	COOPERATOR	SOIL DEPTHS, cm 0-31	31-61	61-91	91-122	122-152	152-183
			ppm NO_3-N†				
1980*	Spratling	3.25	12.68	19.35	4.88	2.29	0.73
1980*	Burnet	2.10	5.00	8.95	9.80	5.35	1.00
1980*	Martin	7.05	4.02	5.10	4.40	2.20	2.40
1981	Spratling	25.72	3.01	2.11	0.97	1.32	2.62
1981	Burnet	18.36	2.37	1.91	2.82	3.33	5.06
1981	Martin	5.84	2.21	2.89	3.57	2.38	0.74
1982	Spratling	28.20	1.87	1.08	0.79	0.79	0.89
1982	Burnet	16.96	2.09	1.38	2.62	2.62	2.62
1982	Martin	12.10	1.82	1.58	1.58	0.94	1.43

†Average of six cores.
*Samples taken in spring, average date March 26, 1980.

Soil water content was measured in the field with the neutron moderation method. From three to five aluminum tubing access tubes were installed in each field at the beginning of the experiment. They were capped 30 cm below the soil surface during the tillage season. After the wheat was seeded and approximately 13 mm of precipitation had settled the loose soil in the ridges, the neutron meter access tubes were located, 38-cm extension tubes put in place to bring the access tubes to the surface and the soil profile water content determined. Water content was measured at approximately monthly intervals during the winter to early March when active growth started. Thereafter, soil water content was measured at approximately biweekly intervals through wheat harvest.

When the cooperator seeded the wheat, soil samples were taken for gravimetric soil water determinations in the seed row to a depth of 18 cm by 2-cm increments to accurately determine depth of seeding and soil water content in the seed zone.

IV. PLANT INFORMATION

Seedling Count and Growth Stage

Seedling counts were taken after emergence and before tillering by counting the seedlings in randomly selected meter lengths of rows. Average growth

stages were estimated using the Zadoks (13) and Tottman (10) scales every time the field sites were visited to obtain samples for total dry matter determination and soil water content, and to check the climate monitor logger.

Aboveground Dry Matter

Aboveground dry matter was measured at approximately biweekly intervals from 10 or 12 areas. The sample area was 3 or 4 adjacent rows by the length required to equal one square meter. Number of rows sampled was dependent on row spacing because the sample area was maintained approximately square. Plants were cut at the soil surface, bagged in cloth bags, transported to the laboratory, weighed, ovendried at 55°C and weighed after drying. Small subsamples were ground, stored and analyzed for total N concentration in the plant tissue. Growth stage also was determined at sampling.

Plant Height

Plant height was measured and recorded whenever aboveground dry matter determinations were made. Heights of the plants were recorded both as canopy height and as extended plant height by extending the leaves to their maximum height above the ground until the spike had developed beyond the extended flag leaf. Thereafter, plant height was measured to the top of the spike. Recorded heights are the average of four measurements.

Grain and Straw Yields

Plants from ten or twelve plots (each 1 m^2 in area and 3 or 4 rows depending on row spacing) were cut at the soil surface when the grain was binder ripe, placed in paper bags, transported to the laboratory, ovendried at 55°C, weighed and threshed. After the grain was cleaned, ovendried and weighed, straw yield was estimated as the difference between plant and grain yield. Subsamples of grain and straw were kept for analyses. Grain yields and test weight per bushel were also taken with a small plot combine by harvesting the grain in 10 or 12 small plots (2.13 x 18 m) adjacent to the 1 m^2 plots.

Components of Yield

Components of yield (number of heads per unit area, number of kernels per head, and kernel weight) were determined on plants harvested from 30 or 50 cm of row adjacent to the ten or twelve 1 m^2 sites hand harvested for yield. In 1980, each head from the 30 cm of row was threshed separately and the kernels counted and weighed to obtain kernels per head and kernel weight. In 1981 and 1982, the heads from 50 cm of row were harvested, counted, bulked, threshed, kernels weighed and counted with an electronic seed counter. These data were used to calculate heads per m^2, average kernels/head, and average weight per kernel.

Nitrogen Concentration

Nitrogen concentration in dry plant material and grain was determined colorimetrically with the Technicon Autoanalyzer (9). Grain protein was computed as the product of the N concentration and the factor 5.7 and adjusted on the basis of 14 percent grain moisture.

V. RADIATION MEASUREMENTS

Spectral reflectance measurements were

taken with a hand-held three-band radiometer on the dates that plant samples were taken if there were no clouds in the sky. The radiometer was hand-held about 1.5 m above the ground level over the wheat. Readings were taken as follows: Two blackout readings (no light allowed to enter the lenses), three readings over a barium sulfate reflectance standard, three readings over the crop, three standards, and two blackout.

VI. A Campbell Scientific[1] Model CR21-E crop climate monitor micrologger system with sensors was used to monitor climatic parameters at each site. The CR21-E micrologger is a battery powered microcomputer with a real time clock, serial data interface, and a programmable analog-to-digital converter. The micrologger sampled the input signals once every minute and stored the signals according to output programs. Input programs specified the type of signal conditioning and A/D conversion to be done, including linearization of selected input signals. The input signals sampled each minute were integrated for hourly periods and then transferred to an audio cassette recorder for later transfer to computer. Output programs further processed the sensor outputs to obtain daily averages, maximums and minimums which were also transferred to the recorder.

Campbell Scientific Model 101 thermistor air and soil temperature probes packaged in stainless steel were used to sense air and soil temperature. The sensors had time constants of less than five seconds and a precision of $\pm 0.5°C$ in the range -10°C to 60°C.

Relative humidity was sampled using a Model 201 relative humidity sensor of the resistance sulfonated polystyrene type with stainless steel screen, mount and protective shield. The precision was $\pm 4\%$ in the 10 to 100% relative humidity range. Relative humidity sensor-monitored values were checked weekly with psychrometric determinations of relative humidity at the site. All other monitored climatic factors were also routinely checked during weekly visits to each site. Wind speed was sensed with a Model 614 cup anemometer with stainless steel cups, switch closure outputs and a precision of ± 0.15 m/s in a wind speed range of 0.5 to 60 m/s.

Incoming and reflected radiation were measured with Spectran[2] model 4048 pyranometers (180° view angle) that were linear over the range of 0 to 2 solar constants and had sensitivity of 5 mv/solar constant. They were temperature compensated so variation in response was no greater than $\pm 2\%$ over a temperature range of -20°C to +40°C. The pyranometers were cosine corrected so variation in the response was no greater than $\pm 1\%$ for constant direct radiation incident at any azimuth angle from 0 to 360° and responsive over the spectral range 0.3 to 4 microns. Change in calibration over a period of one year was not greater than $\pm 1\%$. The pyranometer measuring reflected radiation was mounted beneath a styrofoam insulated automobile hubcap.

[1] Campbell Scientific, P.O. Box 551, Logan, Utah 84321. Use of trade or product names does not constitute endorsement by the Agricultural Research Service.

[2] Spectron Instruments, P.O. Box 891, La Habra, California 90631.

Net radiation was measured using Fritschen (3) miniature net radiometers with sensitivity sufficient to give a full-scale range of ±1.4 ly/min with a recording sensitivity and accuracy of 0.003 ly/min.

The anemometer and shielded relative humidity air temperature sensors were mounted on opposite ends of a crossarm on a tripod at a height of 1.8 m. The radiation sensors were mounted on leveled 2.5 x 5.0 cm steel tubing 4 meters in length mounted between two steel fence posts anchored in the soil. The level steel tubing with the radiation sensors was periodically adjusted to a height of 15 to 25 cm above the growing crop. Soil temperatures were taken at 0.5- and 3-cm depths beneath the seeded crop.

Tipping bucket rain gauges failed during light misty rains and when hoarfrost occurred. Standard 25-cm forestry type rain gauges with removable funnel and calibrated measuring tube were used. During freezing weather, the funnel and measuring tube were removed and precipitation caught in the overflow can in ethylene glycol with a layer of light oil to control evaporation. Rain gauges were read at approximately weekly intervals.

Insulated leads from the sensors were connected to the CR21-E crop climate monitor micrologger inside a small field shelter (1.5 x 2.0 x 1.6 m). Whenever ambient temperatures neared -10°C during the first winter, the rubber friction drive on the audio cassette recorder failed to function properly. This was corrected in succeeding years by placing the recorder inside a box lined with 6 cm of styrofoam insulation and placing a small thermostat controlled 12-volt light bulb over the recorder. The thermostat closed the bulb circuit when recorder temperature neared -1°C and opened at 5°C.

The crop climate monitor micrologger and appropriate sensors were installed in the fields after seeding and emergence of the crop, and after about 13 mm post-seeding precipitation had settled the loose soil in the ridges between the deep furrow-seeded wheat. This condition usually occurred in November after seeding in October. This procedure prevented burial of young plants in the deep furrows by the loose interfurrow soil in the ridges.

Total incoming, reflected and net radiation; maximum, minimum and mean air temperature; relative humidity; maximum, minimum and mean soil temperatures at 0.5- and 3-cm depths; and wind speed were monitored every minute, integrated hourly and transferred to the tape recorder. At 2400 hour of each day, all of the above-monitored climatic data for the previous 24 hours were integrated and maximum, minimum, total and means for each was transferred to the tape recorder. Tape recorders were collected weekly and the tape data stored on a computer disk and a hard copy printed for inspection. Meteorological data were transmitted to Houston, Texas for compilation and processing (see Chapter 7).

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245

CHAPTER 2. DESCRIPTION OF DATA COLLECTION SITES AND METHODS

E. NORTHERN GREAT PLAINS: SPRING WHEAT

Armand Bauer and J. K. Aase[1]

Information and data on spring wheat were collected from 16 farm fields over a 3-year period. Seven fields were located in the semiarid region and nine in the subhumid. Soils at all locations developed on glacial till and all are medium textured. The farmer cooperator performed all operations in seedbed preparation, seeding, fertilization, pest control and harvesting. Four cooperators participated in each of the three years, 1979-1980-1981.

I. LOCATION INFORMATION

The cooperator name, physical location of each field, elevation and field size are indicated in Table 1. Monthly air temperature and precipitation averages from nearby National Oceanic and Atmospheric Administration (NOAA) weather stations, number of frost-free days, and date of first spring and first fall freeze are provided in Table 2. A description of sensors and data acquisition systems to monitor on-site climatic elements on an hourly or less frequent interval is provided in Chapter 3. Atmospheric data were sent to Houston, TX for compiling and processing (Chapter 7). Information on probability of freeze occurrence in the spring and fall is provided by Sanderson (1963) and of frost-free days by Ramirez (1972).

II. MANAGEMENT INFORMATION

Information on some of the management details are provided in Table 3.

III. SOIL CHARACTERISTICS

Soil associations for each field are depicted in Figures 1 through 8 accompanied by a SOIL SURVEY LEGEND. The soil series descriptions are given in soil survey reports (Pescado and Brockman, 1980; Seago et al., 1970; Stout et al., 1974).

A. Physical measurements

Soils are sampled after spring tillage and seeding. Soil samples were removed in 30.5 cm increments to 183 cm at 6 to 8 points in each field with a Giddings probe[2] and immediately placed into double plastic bags to prevent water loss. Core diameter was 3.81 cm. The entire core soil mass was included in the sample at North Dakota sites, and soil mass from the center 15 cm at the Montana sites. Sampling points were selected to represent the dominant soils, with frequency of series representation based on the approximate areal proportion of the soil in the field. Steel electrical conduit was installed at each point to serve as access to measure soil water by neutron attenuation (Stone et al., 1955).

In the laboratory, the soil mass of each increment was weighed. Then a sub-sample was removed, weighed, and oven-dried at 105 to 110°C for 24 hrs, to measure water concentration. The remaining soil was air dried, then crushed to pass a 2-mm sieve. Bulk density was calculated from the known core volume and oven-dry soil mass (Blake, 1965). Data of soil bulk

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[1] Soil Scientists, Agricultural Research Service, U. S. Department of Agriculture, Mandan, ND and Sidney, MT, respectively.

[2] Use of trade or product names does not constitute endorsement by the Agricultural Research Service.

Table 1. Cooperator identification, physical location of each field, approximate elevation, and field size.

Cooperator	Year	County	Section	Township†	Range†	Latitude		Longitude		Elevation	Field size
						deg	min	deg	min	m	ha
Thorson	1979	Burleigh, ND	S1/2 NE1/4 18	141	76	47	05	100	20	580	20
Marquart	1979	Nelson, ND	NE1/4 20	152	61	47	57	98	29	425	20
Birst	1979	McLean, ND	SE1/4 2	148	81	47	40	100	56	550	16
Winter	1979	Sheridan, ND	W1/2 NE1/4 9	147	74	47	34	100	98	485	32
Heinz	1979	McKenzie, ND	NE1/4 18	151	100	47	54	103	31	640	19
Ystaas	1979	Wells, ND	N1/2 N1/2 15	150	68	47	49	99	20	444	21
Rasmussen	1979	Richland, MT	E1/2 SE1/4 16	23	58	47	45	104	16	680	32
McCabe	1979	Roosevelt, MT	W1/2 NW1/4 8	30	56	48	22	104	28	610	30
Thorson	1980	Burleigh, ND	SE1/4 24	141	77	47	05	100	20	580	24
Marquart	1980	Nelson, ND	NE1/4 20	152	61	47	57	98	29	425	38
Winter	1980	Sheridan, ND	NW1/4 9	147	74	47	34	100	08	485	24
Ystaas	1980	Wells, ND	NW1/4 14	150	68	47	49	99	20	455	32
Thorson	1981	Burleigh, ND	E1/2 SW1/4 8	141	76	47	05	100	20	580	30
Marquart	1981	Nelson, ND	NE1/4 20	152	61	47	57	98	29	425	20
Winter	1981	Sheridan, ND	SW1/4 9	147	74	47	34	100	8	485	16
Ystaas	1981	Wells, ND	NE1/4 14	150	68	47	49	99	20	455	32

† For North Dakota, the 5th Principal Meridian and 40° north latitude are the base lines for range and township designations, respectively. In Montana, the Montana Principal Meridian and Montana Base Line are the base lines.

Table 2. Average monthly air temperature and precipitation recorded at NOAA weather station near the field sites, number of frost free days, and date of spring and fall freeze.

Month	Bismarck,†ND		Devils Lake,‡ND		McClusky,‡ND		Minot,†ND		Williston,†ND		Sidney,§MT	
	C°	mm	C°	mm	C°	mm	C°	mm	C°	mm	C°	mm
Jan	-13	13	-15	14	-14	14	-14	18	-13	14	-13	10
Feb	-10	11	-13	10	-11	11	-10	15	-12	13	- 8	10
Mar	- 2	18	- 6	22	- 5	20	- 4	20	- 4	15	- 2	12
Apr	6	38	4	28	5	41	5	45	6	33	6	29
May	12	57	11	58	12	53	12	59	12	47	13	52
June	18	76	17	86	17	99	17	83	17	68	17	72
July	22	52	21	58	21	58	21	58	21	46	21	45
Aug	21	43	19	54	20	52	19	52	20	36	19	42
Sep	14	35	13	53	14	42	13	49	14	35	14	33
Oct	8	21	7	23	8	21	7	22	7	19	8	22
Nov	- 2	13	- 3	16	- 2	15	- 2	15	- 2	13	- 1	11
Dec	- 9	13	-12	14	-10	13	- 9	18	- 9	14	- 8	11
Total		390		436		439		454		353		350
Frost-free days	125		120		125		120		125		125	
Spring¶ freeze	May 11		May 17		May 22		May 21		May 13		May 13††	
Fall # freeze	Sep 22		Sep 21		Sep 17		Sep 15		Sep 24		Sep 24††	
Lat.	46° 46'		48° 07'		47° 29'		48° 16'		48° 11'		47° 43'	
Long.	100° 46'		98° 52'		100° 28'		101° 17'		103° 38'		104° 07'	

† 1951-1980 average
‡ 1941-1970 average
§ 1949-1982 average
¶ 50% probability of freeze occurring after the indicated date.
# 50% probability of freeze occurring before the indicated date.
†† No date available. Sidney is about 60 km from Williston.

Table 3. Management information for each location.

Cooperator	Previous Crop	Cultivar	Row Spacing	Row Orientation	Seeding Rate	Fertilization Rate	Seeding Date	Harvest Date	Yield Estimate#
			cm		kg/ha	kg/ha N-P-K	- - - day/mo/yr	- - - -	kg/ha
Thorson	Fallow†	Wared	15	E-W	84	0-0-0	14 May 1979	16 Aug 1979	1410
Marquart	Fallow	Cando¶	15	N-S	100	16-7-0	29 May 1979	05 Sep 1979	3560
Birst	Oats	Waldron	15	N-S	84	9-10-0	24 May 1979	14 Aug 1979	940
Winter	Fallow	Ellar	15	N-S	67	10-11-6	01/June 1979	29 Aug 1979	1680
Heinz	Fallow	Butte	15	E-W	84	9-10-0	18 May 1979	29 Aug 1979	1475
Ystaas	Fallow	Butte	15	E-W	100	28-12-0	15 June 1979	(Hailed out)	††
Rasmussen	Fallow	Olaf	15	N-S	56	8-16-0	22 May 1979	22 Sep 1979	1545
McCabe	Fallow	Cando	18	N-S	84	10-10-0	03 June 1979	15 Sep 1979	1000
Thorson	Fallow	Solar	15	§	84	0-0-0	22 April 1980	31 July 1980	‡‡
Marquart	Fallow	Cando	15	N-S	100	16-7-0	30 April 1980	04 Aug 1980	2015§§
Winter	Fallow	Ellar	15	N-S	67	10-11-6	02 May 1980	11 Aug 1980	1680§§
Ystaas	Fallow	Len	15	N-S	91	72-12-0	02 June 1980	08 Sep 1980	2685
Thorson	Fallow-Wheat ‡	Len	15	N-S	84	0-0-0	16 April 1981	06 Aug 1981	1680
Marquart	Wheat	Ward	15	N-S	100	45-12-0	23 April 1981	07 Aug 1981	3360
Winter	Fallow	Cando	15	E-W	67	10-11-6	07 May 1981	17 Aug 1981	2285
Ystaas	Fallow	Len	15	§	100	28-12-0	19 May 1981	26 Aug 1981	3025

† Winter wheat seeded on fallow in the fall was winterkilled. The Wared wheat was then seeded on the field in the spring.
‡ About 50% on fallow.
§ Circled field.
¶ Durum. Other varieties are hard red spring wheats.
# Cooperator's estimate based on harvest of entire field.
‡‡ Crop was swathed, but it was not harvested by the cooperator because of excess water.
§§ Harvest yield losses because of excess rainfall while in windrows.
†† Not harvested because of hail.

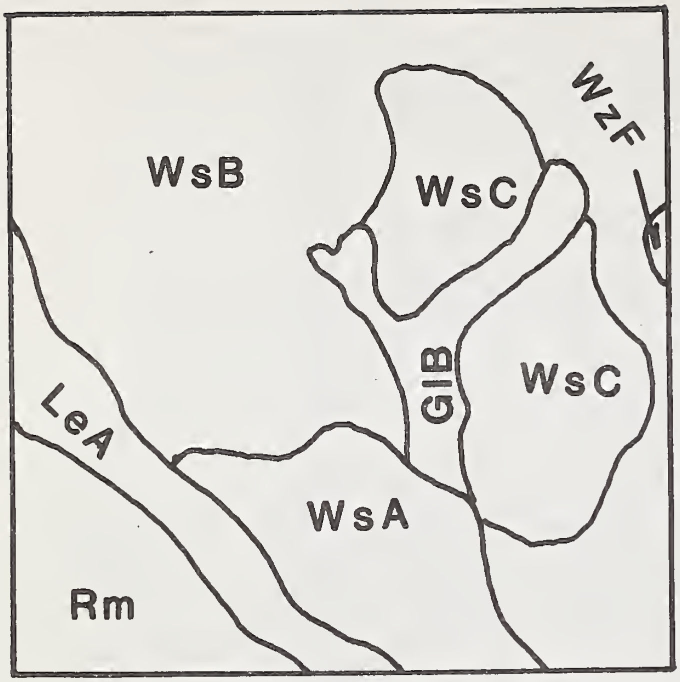

Figure 1a. Soil survey map of NE1/4 18 T141 R76, Thorson 1979 site. The field sampled was in the south half of the quarter section.

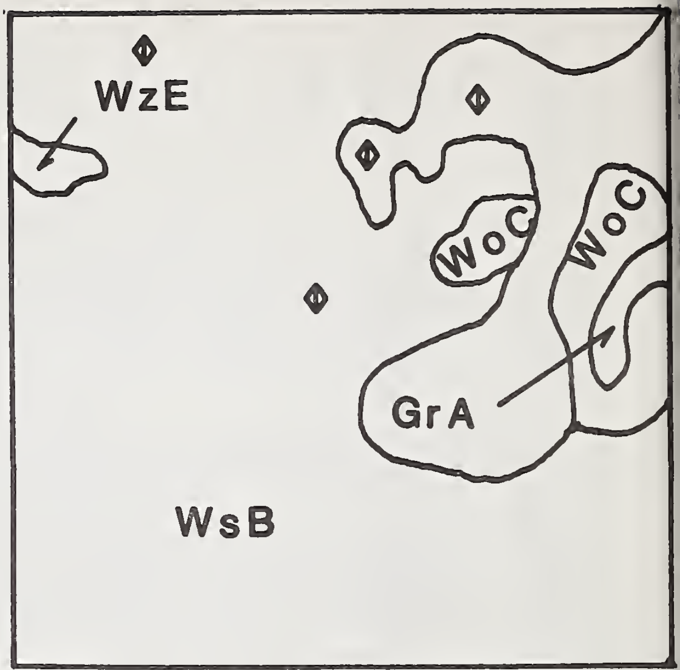

Figure 1b. Soil survey map of SE1/4 24 T141 R77, Thorson 1980 site. The field sampled was in the west half of the quarter section.

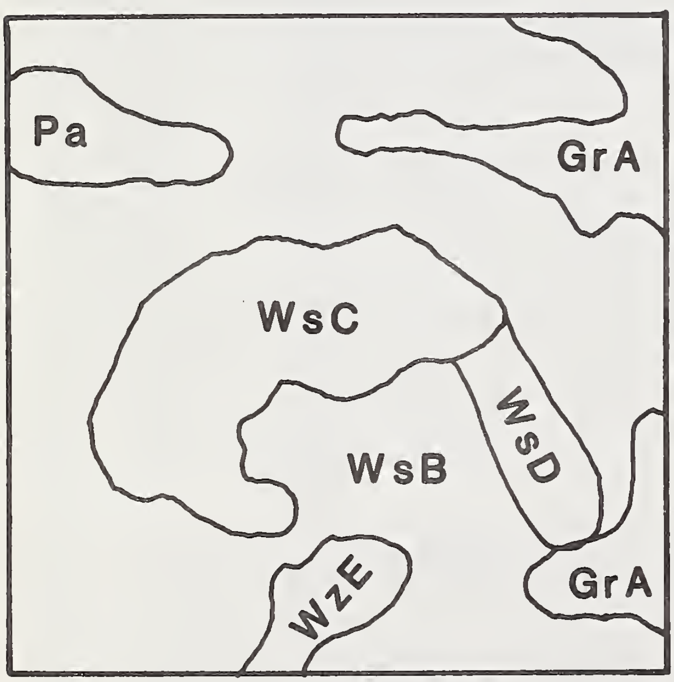

Figure 1c. Soil survey map of SW1/4 8 T141 R76, Thorson 1981 site. The field sampled was in the east half of the quarter section.

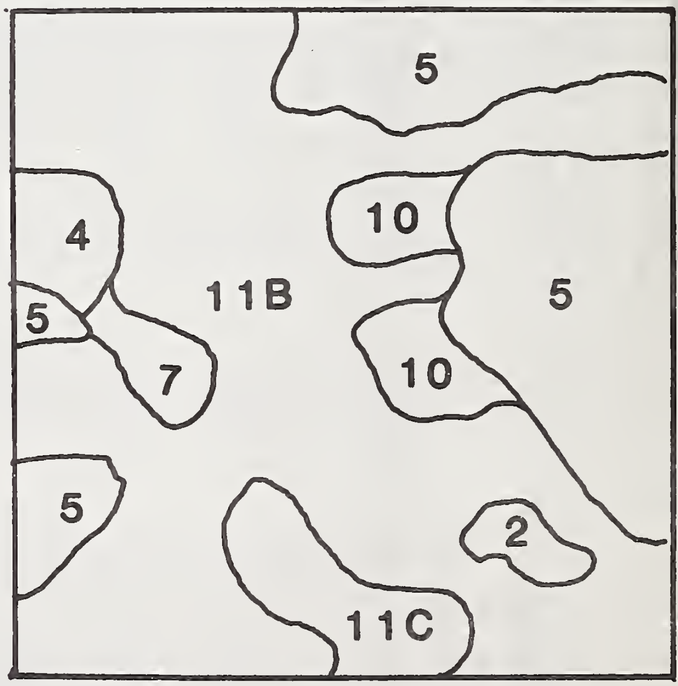

Figure 2. Soil survey map of NE1/4 20 T152 R61, Marquart 1979, 1980, and 1981 sites. The field sampled in 1979 was in the west half of the quarter section, and in 1980 and 1981 in the east half.

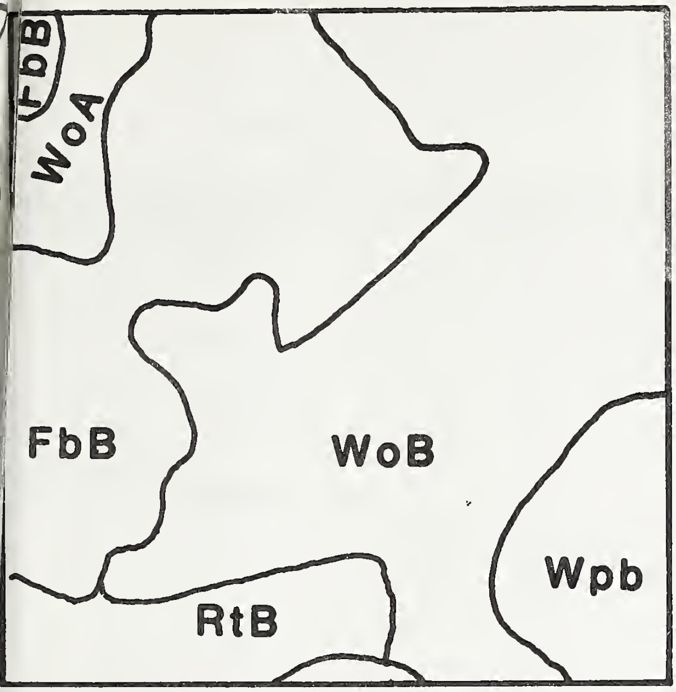

Figure 3. Soil survey map of SE1/4 2 T148 R81, Birst 1979 site. The field sampled was in the east half of the quarter section.

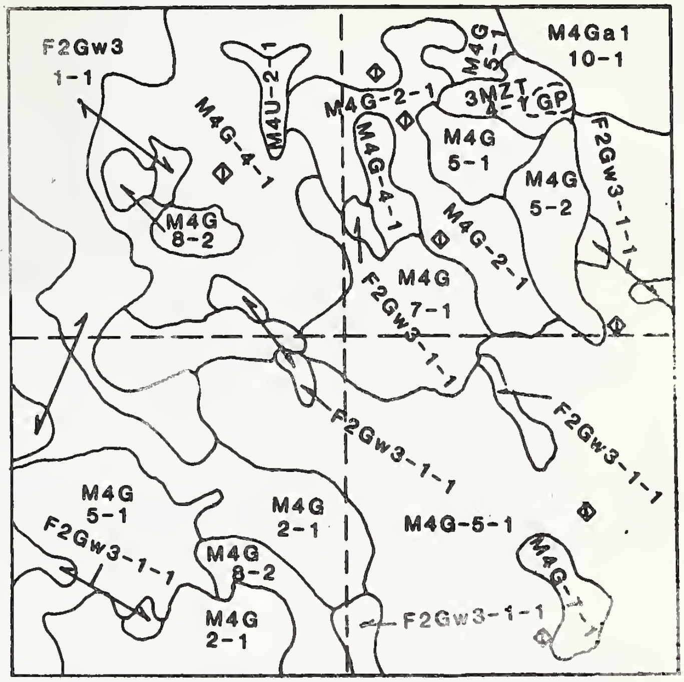

Figure 4. Soil survey map of section 9 T147 R74, Winter 1979, 1980 and 1981 sites. The field sampled in 1979 was in the west half of the NE1/4; in 1980 the field sampled was in the east half of the NW1/4; and in 1981 the S1/2 of the SW1/4.

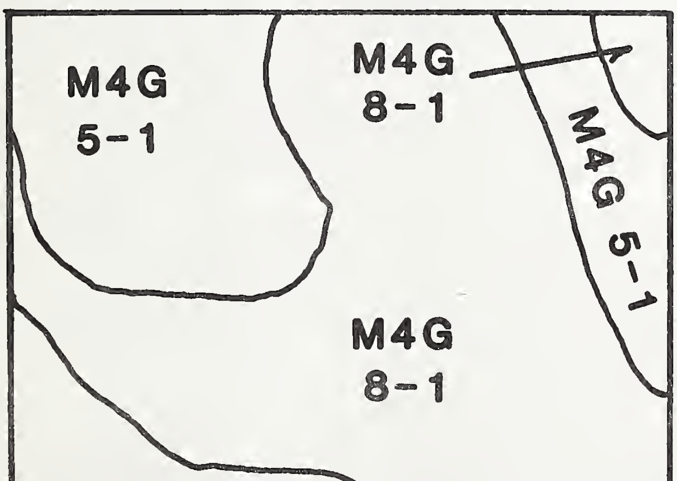

Figure 5. Soil survey map of NE1/4 18 T151 R100, Heinz 1979 site. The field sampled was in the south half of the quarter section.

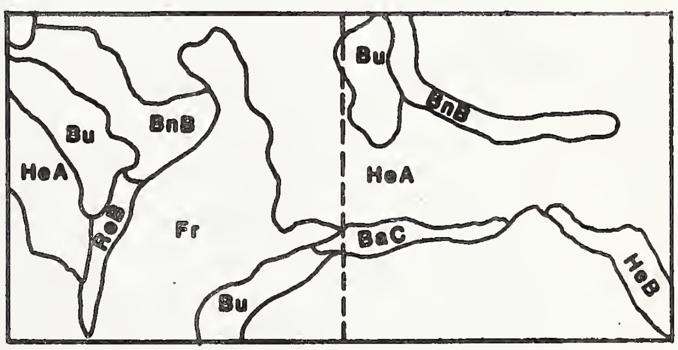

Figure 6a. Soil survey map of the N1/2 of section 15 T150 R68, Ystaas 1979 site. The field sampled was in the S1/2 of the N1/2 of the section.

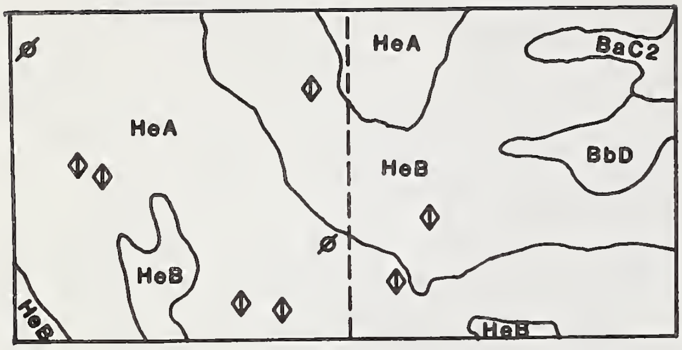

Figure 6b. Soil survey map of the N1/2 of section 14 T150 R68, Ystaas 1980 and 1981 sites. The field sampled in 1980 was in the east half of the NW1/4; in 1981 the field was in the S1/2 of the NE1/4.

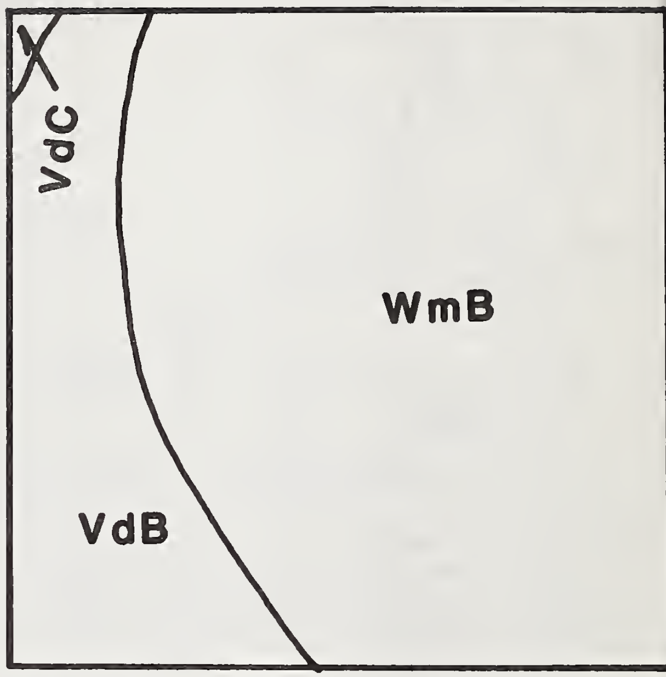

Figure 7. Soil survey map of the SE1/4 16 T23 R58, McCabe 1979 site. The field sampled was in the E1/2 of the quarter section.

Figure 8. Soil survey map of NW1/4 8 T30 R56, Rasmussen 1979 site. The field sampled was in the W1/2 of the quarter section.

SOIL SURVEY LEGEND

Site	Symbol	Soil, slope
Thorson	W_sA	Williams loam, 0 to 3 percent
	W_sB	Williams loam, 3 to 6 percent
	W_sC	Williams loam, 6 to 9 percent
	W_sD	Williams loam, 9 to 12 percent
	W_zE	Williams-Zahl loams, 9 to 12 percent
	GrA	Grail silty clay loam, 0 to 3 percent
	GlB	Grail silt loam, 3 to 6 percent
	LeA	Lehr loam, 0 to 3 percent
Marquart	2	Parnell silt loam, 0 to 1 percent
	4	Rauville silty clay loam, ponded
	5	Hamerly-Tonka loams, 0 to 3 percent
	7	Parnell-Vallers loams, 0 to 3 percent
	10	Svea loam, 1 to 3 percent
	11B	Svea-Buse loams, 3 to 6 percent
	11C	Svea-Buse loams, 6 to 9 percent
Birst	WoA	Williams-Bowbells loams, 1 to 3 percent
	WoB	Williams-Bowbells loams, 3 to 6 percent
	WpB	Williams-Bowbells-Zahl loams, 3 to 6 percent
	FbB	Falkirk-Max loams, 3 to 6 percent
	RtB	Russo-Manning coarse sandy loams, 3 to 6 percent
Winter	M4G-2-1	Barnes-Svea loams, 1 to 3 percent
	M4G-4-1	Barnes-Svea loams, 3 to 6 percent
	M4G-5-1 (5-2)	Barnes-Svea loams, 3 to 6 percent
	M4G-7-1 (8-2)	Barnes-loam, 6 to 9 percent
	M4U-2-1	Arnegard loam, 1 to 3 percent
	$F2GS_3$-1-1	Parnell silt loam, 0 to 1 percent
	M4Ga1-10-1	Buse-Barnes loams, 9 to 15 percent
	3MZT-4-1	Renshaw loam, 3 to 6 percent
Heinz	M4G-5-1	Williams loam, 3 to 6 percent
	M4G-8-1	Williams loam, 6 to 9 percent
Ystaas	HeA	Heimdal-Emrick loams, 0 to 3 percent
	HeB	Heimdal-Emrick loams, 3 to 6 percent
	BnB	Barnes-Svea loams, 3 to 6 percent
	Bu	Borup loam, 0 to 1 percent
Rasmussen	WmB	Williams loam, 0 to 4 percent
	VdB	Vida clay loam, 1 to 4 percent
	VdC	Vida clay loam, 4 to 8 percent
	VhD	Vida-Zahill complex, 8 to 15 percent
	ZaF	Zahill loam, 15 to 65 percent
	BkB	Banks loamy fine sand, 0 to 4 percent
McCabe	28B	Williams loam, 2 to 8 percent
	36B	Grail silty clay loam, 0 to 4 percent
	35B	Havre silty clay, 2 to 8 percent
	228B	Williams-Zahill loam, 2 to 8 percent

density are given in Table 4.

Soil water characteristics were determined at 4 to 7 pressures over the range of 0.010 to 1.5 MPa (Richards, 1947) on soil samples passed through a 2-mm sieve. These data, average of all sampled points, are given in Table 5.

Data of available water capacity (AWC) for specific sites and years are presented in Table 6. The AWC was calculated from water concentration at 0.033 MPa and 1.5 MPa (Table 5), and bulk density (Table 4).

$$AWC = \frac{(0.33 \text{ MPa} - 1.5 \text{ MPa})\ (Bd)\ (Z)}{(100)\ (Wd)} \quad [1]$$

where Bd is bulk density, Z is soil increment thickness, and Wd is water density. The density of water is approximated as 1.00 g cm^{-3}

Soil water content in the field was measured on approximately a weekly basis. Water held at a tension of 1.5 MPa and less was considered as available to plants. Data of available soil water for specific sites and years were compiled at Houston, TX (Chapter 7).

Chemical measurements

Nitrate and ammonium concentration were measured on soil samples removed at the point of access tube installation at North Dakota sites. At the time of sampling, any fertilizers applied to the crop were already on the land. Extraction and detection procedures were those described by Bremner (1965a). Data of NO_3-N and NH_4-N are presented in Table 7.

Total N (Bremner, 1965a), organic C (Allison, 1965), $NaHCO_3$ soluble P (Olsen et al., 1954), and total P (Olsen and Dean, 1965) were measured on samples removed in 10 cm increments to 40 cm and from the 40- to 60-cm depth, from the moderately well drained landscape position normally occupied by the Barnes and Williams soil series. Data of these soil properties are presented in Tables 8a through 8f.

IV. PLANT INFORMATION (data not presented)

Seedling count and growth stage

Twelve one m^2 areas were "permanently" staked in each field after seedling emergence. The seedlings were counted in each m^2 area before tillering began. (Axillary tillers appear at the 3-leaf stage.) Estimates of growth stage were made by observing the plants in these "permanent" areas, using either or both the Haun and Feekes scale (Bauer et al., 1983). The stakes were left in place until harvest. These 12 areas were representative of the dominant soils, with the frequency of representation based on the approximate areal proportion of each soil in the field. Each m^2 area was positioned over 5- or 6-row widths, and attempts were made to position all 12 areas on the same drill rows.

Aboveground dry matter

Aboveground dry matter was measured on 12 one m^2 samples removed from positions in close proximity to the "permanent" staked areas. Tissue was cut at soil surface level and transported to the laboratory in cloth bags. The green tissue was weighed, oven-dried at 69°C, and weighed after oven-drying.

Table 4. Average bulk density at six soil depths.†

Year	Cooperator	Soil depth (cm) 0-31	31-61	61-91	91-122	122-152	152-183
		------------ $g\ cm^{-3}$ ------------					
1979	Marquart	1.09	1.34	1.49	1.42	1.58	1.61
	Thorson	1.24	1.53	1.56	1.52	1.61	1.60
	Heinz	1.11	1.24	1.36	1.32	1.36	1.35
	Winter	1.19	1.42	1.57	1.55	1.58	1.67
	Birst	1.17	1.35	1.48	1.51	1.61	1.58
	Ystaas	1.18	1.35	1.56	1.72	1.82	1.92
	Rasmussen	1.50	1.53	1.66	1.73	1.70	1.77
	McCabe	1.52	1.53	1.69	1.69	1.84	1.75
1980	Thorson	1.17	1.41	1.52	1.54	1.64	1.45
	Winter	1.13	1.34	1.52	1.50	1.57	1.62
	Marquart	1.12	1.44	1.36	1.42	1.50	1.55
	Ystaas	1.05	1.20	1.34	1.47	1.66	1.66
1981	Marquart	0.79	1.22	1.47	1.49	1.53	1.53
	Ystaas	1.25	1.38	1.40	1.63	1.66	1.68
	Thorson	0.88	1.37	1.48	1.42	1.40	1.34
	Winter	1.25	1.40	1.51	1.69	1.72	1.65

† Average of 8 points at Thorson in 1981, and 6 points at all others.

Table 5. Water desorption values for designated soil depths after equilibration at specified pressures.†

Year	Cooperator	Pressure	Soil depth (cm) 0-31	31-61	61-91	91-122	122-152	152-183
		MPa	% water by weight					
1979	Marquart	0.033	30.21	30.08	28.57	28.85	25.97	25.75
		0.100	24.31	24.23	23.57	22.79	21.62	21.22
		0.500	19.12	19.28	18.98	17.44	16.46	16.79
		1.500	15.78	15.49	15.06	14.24	13.14	13.34
	Thorson	0.033	19.39	19.36	22.52	26.08	25.01	25.96
		0.100	14.41	14.69	17.73	20.94	19.51	21.28
		0.500	11.28	12.11	14.01	17.32	15.98	16.06
		1.500	08.46	09.12	10.33	11.95	11.00	11.40
	Heinz	0.033	17.11	20.47	20.27	25.02	25.44	25.26
		0.100	13.50	15.92	16.35	19.70	20.18	20.36
		0.500	10.71	12.14	13.32	15.37	15.80	16.63
		1.500	08.38	09.15	10.18	11.58	11.86	12.41
	Winter	0.033	26.33	26.55	25.98	26.03	27.65	28.22
		0.100	19.75	19.94	19.94	20.09	20.72	21.39
		0.500	15.00	15.91	15.00	14.95	15.93	16.14
		1.500	12.77	12.61	11.82	11.62	12.03	12.28
	Birst	0.033	21.92	22.04	19.44	21.44	20.84	23.04
		0.100	15.97	16.83	15.84	14.41	15.43	17.21
		0.500	12.53	13.17	11.87	11.18	11.50	12.78
		1.500	10.04	09.26	08.62	08.78	09.06	09.91
	Ystaas	0.033	24.72	19.74	19.15	18.61	17.96	18.86
		0.100	18.01	14.49	14.98	14.38	13.68	15.21
		0.500	13.68	11.92	11.79	11.24	09.88	10.95
		1.500	11.53	08.95	07.96	07.99	07.26	08.33
	Rasmussen	0.010	32.99	33.34	32.01	33.64	26.60	
		0.033	20.18	21.89	22.97	24.01	18.33	
		0.100	16.58	18.16	19.26	19.31	15.00	
		0.200	13.53	15.00	15.29	16.37	12.26	
		0.300	12.75	14.07	14.33	15.09	11.85	
		0.800	10.17	10.87	11.17	12.10	08.61	
		1.500	09.57	09.79	10.35	10.55	08.64	
	McCabe	0.010	27.62	28.32	26.79	30.44	26.95	
		0.033	16.51	20.26	17.63	21.79	19.08	
		0.100	12.73	16.90	14.34	17.79	15.18	
		0.200	10.97	13.72	12.25	15.07	12.80	
		0.300	10.24	13.25	10.87	13.94	12.24	
		0.800	08.20	09.97	09.08	11.34	10.28	
		1.500	07.98	09.39	08.12	10.71	08.91	

Year	Cooperator	Pressure MPa	Soil depth (cm) 0-31	31-61	61-91	91-122	122-152	152-183
			% water by weight					
1980	Thorson	0.033	22.69	20.83	19.93	21.93	22.99	26.04
		0.100	18.78	16.97	16.23	18.20	18.48	21.38
		0.500	15.09	14.29	13.16	14.54	14.97	18.28
		1.500	12.51	11.44	10.52	11.70	12.63	14.23
	Winter	0.033	22.98	22.67	23.49	22.06	23.61	24.20
		0.100	18.98	18.66	18.53	17.95	19.53	19.89
		0.500	15.29	15.23	14.37	14.51	15.10	15.10
		1.500	12.15	11.78	11.09	10.91	11.47	11.77
	Marquart	0.033	27.41	24.05	25.06	25.16	23.01	25.36
		0.100	23.92	21.01	20.77	21.39	18.75	21.78
		0.500	18.99	16.98	16.13	15.67	14.39	17.01
		1.500	16.18	13.55	12.67	12.35	11.51	13.32
	Ystaas	0.033	25.79	22.01	20.95	19.81	17.86	15.65
		0.100	21.09	18.25	17.47	16.02	14.74	13.05
		0.500	15.50	14.13	12.27	11.33	11.24	09.67
		1.500	12.56	10.27	09.64	08.82	08.49	07.99
1981	Marquart	0.033	32.85	27.64	25.08	26.63	28.76	27.17
		0.100	24.95	20.35	19.47	22.05	21.78	22.73
		0.500	21.58	17.64	17.06	17.71	19.01	18.83
		1.500	18.09	13.72	13.73	14.97	16.09	15.69
	Ystaas	0.033	24.14	21.31	20.00	20.00	17.99	16.91
		0.100	17.52	15.83	15.10	15.19	12.68	12.31
		0.500	13.73	12.14	11.14	11.02	08.79	08.71
		1.500	12.09	10.28	08.95	08.80	06.99	06.64
	Winter	0.033	24.13	24.22	25.40	26.11	26.61	27.18
		0.100	18.49	18.80	20.24	21.03	21.13	21.77
		0.500	15.23	15.38	16.82	16.63	16.49	17.31
		1.500	13.02	12.56	13.06	13.38	13.13	13.15
	Thorson	0.033	34.88	34.71	35.13	37.39	39.60	44.05
		0.100	26.66	26.65	27.41	29.70	31.24	32.45
		0.500	22.08	22.04	22.53	24.53	26.32	28.26
		1.500	17.40	17.17	16.89	18.11	18.64	20.06

† Average of 8 points at Thorson in 1981, and 6 points at all others.

Table 6. Available water capacity for designated soil depths.†

Year	Cooperator	Soil depth (cm) 0-31	31-61	61-91	91-122	122-152	152-183
1979	Marquart	4.88	5.87	6.04	6.43	6.08	6.19
	Thorson	4.20	4.70	5.70	6.66	6.77	7.22
	Heinz	3.00	4.21	4.12	5.50	5.54	5.38
	Winter	5.00	5.94	6.67	6.92	7.40	8.25
	Birst	4.31	5.18	4.80	5.93	5.69	6.43
	Ystaas	4.82	4.37	5.24	5.66	5.84	6.27
	Rasmussen	4.93	5.55	6.28	7.22	4.94	--
	McCabe	4.02	4.99	4.82	5.80	5.61	--
1980	Thorson	3.69	3.97	4.29	4.88	5.10	5.31
	Winter	3.79	4.38	5.65	5.18	5.72	6.24
	Marquart	3.90	4.54	5.06	5.64	5.18	5.79
	Ystaas	4.31	4.23	4.55	5.01	4.67	3.94
1981	Thorson	4.77	7.21	8.10	8.49	8.80	9.97
	Winter	4.31	4.90	5.59	6.67	6.96	7.18
	Marquart	3.61	5.09	5.01	5.39	5.82	5.44
	Ystaas	4.67	4.57	4.64	5.66	5.48	5.35

† Average of 8 points at Thorson in 1981, and 6 points at all others.

Table 7. Nitrate and ammonium concentration at six soil depths at points of access tube installation.

Year	Cooperator	Soil depth (cm)					
		0-31	31-61	61-91	91-122	122-152	152-183
		ppm NO_3N†					
1979	Winter	33.49	15.53	8.45	14.56	18.40	17.50
1979	Thorson	30.70	12.41	4.11	4.69	2.75	2.36
1979	Birst	9.93	5.24	7.78	6.06	2.43	3.31
1979	Ystaas	46.65	10.43	6.83	2.98	1.47	1.17
1979	Heinz	7.55	5.16	2.14	1.80	1.49	1.76
1979	Marquart	29.70	13.94	10.86	7.86	4.21	3.13
1980	Winter	27.02	8.92	5.90	4.49	3.90	7.34
1980	Thorson	35.54	13.43	11.96	11.69	15.80	19.79
1980	Ystaas	69.06	62.06	3.13	2.34	1.66	1.51
1980	Marquart	53.21	27.33	31.65	16.89	6.53	3.12
1981	Winter	10.41	6.80	8.11	6.54	5.12	2.86
1981	Thorson	15.90	12.41	6.48	16.88	14.31	7.02
1981	Ystaas	20.16	10.05	12.77	6.62	5.87	3.28
1981	Marquart	28.77	15.54	14.10	8.23	5.44	3.18
		ppm NH_4-N†					
1979	Winter	5.94	3.58	3.22	3.07	3.12	2.92
19790	Thorson	5.07	3.19	2.84	3.84	2.29	2.08
1979	Birst	4.41	3.19	2.38	2.32	2.01	2.40
1979	Ystaas	4.60	2.38	1.52	1.41	1.51	1.75
1979	Heinz	3.34	2.90	3.20	3.82	3.92	3.86
1979	Marquart	4.25	2.91	2.08	1.93	1.95	1.87
1980	Winter	5.28	3.60	2.41	2.62	2.80	2.80
1980	Thorson	5.43	3.42	3.08	3.87	3.99	4.00
1980	Ystaas	3.68	2.37	2.01	1.87	1.07	2.33
1980	Marquart	4.10	2.96	2.72	2.28	2.31	2.54
1981	Winter	3.00	2.40	2.15	2.41	2.66	3.05
1981	Thorson	5.93	3.63	2.86	2.73	2.89	3.31
1981	Ystaas	2.97	2.40	2.12	1.94	1.62	1.71
1981	Marquart	5.66	3.44	2.15	2.13	2.03	2.04

† Average of six holes, except at Thorson in 1981.

Table 8a. Total nitrogen (N) concentration at five depths of soil in the moderately well drained landscape position.

Year	Cooperator	Soil depth (cm) 0-10	10-20	20-30	30-40	40-60
		% total N by weight				
1979	Thorson	0.206	0.140	0.095	0.076	0.069
1979	Heinz	0.101	0.084	0.081	0.084	0.080
1979	Birst	0.288	0.183	0.115	0.099	0.086
1979	Winter	0.223	0.193	0.141	0.077	0.067
1979	Ystaas	0.256	0.216	0.133	0.119	0.088
1979	Marquart	0.198	0.203	0.092	0.075	0.052
1980	Thorson	0.244	0.225	0.141	0.110	0.075
1980	Winter	0.235	0.185	0.123	0.098	0.076
1980	Ystaas	0.210	0.193	0.139	0.106	0.074
1980-81	Marquart	0.294	0.334	0.160	0.108	0.108
1981	Thorson	0.235	0.198	0.155	0.083	0.070
1981	Winter	0.260	0.237	0.130	0.083	0.099
1981	Ystaas	0.197	0.190	0.134	0.110	0.069

Table 8b. Organic carbon (C) concentration at five depths of soil in the moderately well drained landscape position.

Year	Cooperator	Soil depth (cm) 0-10	10-20	20-30	30-40	40-60
		% organic C by weight				
1979	Thorson	2.05	1.19	0.83	0.69	0.62
1979	Heinz	0.89	0.67	0.65	0.72	0.69
1979	Birst	2.64	1.78	1.01	0.93	0.86
1979	Winter	2.38	2.07	1.43	0.97	0.59
1979	Ystaas	2.67	2.31	1.27	1.09	0.88
1979	Marquart	2.41	1.94	0.85	0.74	0.57
1980	Thorson	2.14	2.03	1.19	0.99	0.62
1980	Winter	2.30	1.74	1.22	0.85	0.63
1980	Ystaas	2.14	1.95	1.02	0.93	0.76
1980-81	Marquart	3.49	3.42	1.41	0.87	0.86
1981	Thorson	2.22	1.94	1.36	0.91	0.68
1981	Winter	2.56	2.22	1.17	0.78	0.70
1981	Ystaas	2.59	1.74	1.09	0.93	0.73

Table 8c. Sodium bicarbonate soluble phosphorus (P) concentration at five depths of soil in the moderately well drained landscape position.

Year	Cooperator	Soil depth (cm) 0-10	10-20	20-30	30-40	40-60
		ppm P				
1979	Thorson	17.58	4.91	4.01	3.07	3.22
1979	Heinz	14.34	5.68	3.80	3.97	3.36
1979	Birst	8.60	5.51	3.80	3.50	3.95
1970	Winter	13.38	8.33	4.97	3.52	3.21
1979	Ystaas	7.89	5.22	3.80	3.49	3.03
1979	Marquart	7.77	5.40	3.19	3.03	2.56
1980	Thorson	7.28	6.36	3.83	2.73	2.41
1980	Winter	11.52	7.15	4.80	3.82	3.81
1980	Ystaas	9.52	5.68	3.34	2.56	2.39
1980-81	Marquart	16.09	14.57	3.99	3.36	3.05
1981	Thorson	14.65	6.85	2.96	2.96	2.65
1981	Winter	23.17	16.39	6.65	3.83	4.13
1981	Ystaas	7.24	5.82	3.48	3.16	2.55

AgRISTARS SITES (Sample autumn 1982)

Table 8d. Total phosphorus (P) concentration at five depths of soil in the moderately well drained landscape position.

Year	Cooperator	Soil depth (cm) 0-10	10-20	20-30	30-40	40-60
		Total P, ug/g				
1979	Thorson	472	363	367	381	395
1979	Heinz	367	357	375	479	512
1979	Birst	512	420	343	464	553
1979	Winter	525	458	435	533	511
1979	Ystaas	547	508	484	538	517
1979	Marquart	499	375	482	401	397
1980	Thorson	499	492	468	589	535
1980	Winter	539	440	599	533	537
1980	Ystaas	544	517	501	473	528
1980-81	Marquart	561	542	384	405	479
1981	Thorson	637	629	634	633	637
1981	Winter	569	531	399	597	372
1981	Ystaas	530	493	495	602	573

Table 8e. Inorganic phosphorus (P) concentration at five depths of soil in the moderately well drained landscape position.

Year	Cooperator	Soil depth (cm) 0-10	10-20	20-30	30-40	40-60
		Inorganic P, ug/g				
1979	Thorson	190	136	144	216	271
1979	Heinz	212	212	250	344	404
1979	Birst	174	165	175	266	386
1979	Winter	194	157	212	391	439
1979	Ystaas	201	212	250	299	366
1979	Marquart	230	253	351	326	347
1980	Thorson	193	197	218	347	377
1980	Winter	233	157	237	335	392
1980	Ystaas	262	262	262	292	373
1980-81	Marquart	192	198	159	269	332
1981	Thorson	328	329	423	465	506
1981	Winter	210	172	132	402	245
1981	Ystaas	250	231	273	388	416

Table 8f. Organic phosphorus (P) concentration at five depths of soil in the moderately well drained landscape position.

Year	Cooperator	Soil depth (cm) 0-10	10-20	20-30	30-40	40-60
		Organic P, ug/g				
1979	Thorson	282	227	223	165	124
1979	Heinz	155	145	125	135	108
1979	Birst	338	255	168	198	167
1979	Winter	331	301	223	142	72
1979	Ystaas	346	296	234	239	151
1979	Marquart	269	122	131	75	50
1980	Thorson	306	295	250	242	158
1980	Winter	306	283	362	198	145
1980	Ystaas	282	255	239	181	155
1980-81	Marquart	369	344	225	136	147
1981	Thorson	309	300	211	168	131
1981	Winter	359	359	267	195	127
1981	Ystaas	280	262	222	214	157

Tillers per plant

Twenty consecutive plants were pulled from a row immediately adjacent to each area from which the aboveground dry matter was harvested. Tillers with green leaves were included in the count. Tillers per m^2 were calculated from seedling population of the nearest "permanent" m^2 area.

Green leaf area index (LAI)

Tissue was cut at soil surface level from approximately 0.5 m of a row immediately adjacent to the "permanent" staked areas, placed in a plastic bag and refrigerated at about 3°C (in a Koolatron[4]) while enroute to the laboratory. At the laboratory, the tissue was weighed and separated into the components of leaves, stems, and heads (as appropriate). Each component was weighed to obtain the weight distribution of each within the sample. The area of green leaf tissue was measured with a LiCor[4] leaf area meter.

The weight distribution of plant components determined for the approximate 0.5 m of row sample and the measured leaf area of their known weight were estimated to apply to the nearest m^2 sample harvested for dry matter yield. The LAI was calculated from the known weight of leaves of the approximate 0.5 m of row sample and their measured leaf area (LA), and the estimated weight of green leaves (GLW) of the m^2 sample.

$$\mathrm{LAI} = \frac{(\mathrm{GLW})\ \ (\mathrm{LA})}{(\mathrm{GLW})} \times 10^{-4} \qquad [2]$$

[4] Use of trade or product name does not constitute endorsement by the Agricultural Research Service.

Plant height

Height, distance from the soil surface to the tip of the spike, was measured at harvest. The recorded height is an average of 3 or 4 measurements within each of 24 one m^2 area harvested for yield estimates.

Spike count

The number of spikes was counted at harvest in the 12 "permanently" staked one m^2 areas and an additional 12 one m^2 areas selected at harvest. All spikes were included. The additional 12 one m^2 areas selected at harvest were distributed over the field on the dominant landscape positions.

Grain and straw yield

Tissue was cut at the soil surface of 24 one m^2 areas, described under "Spike count", and transported to the laboratory in cloth bags. The tissue was oven-dried at 69°C, weighed, and threshed.

The grain was cleaned, oven-dried, and weighed. Straw yield was estimated as the difference between the harvested tissue yield and grain yield.

Spikes (Heads) per plant

Spikes per plant is the quotient of number of spikes at harvest in the 12 "permanently" staked one m^2 areas divided by number of seedlings counted in the same area.

Kernel weight

Kernel weight, oven-dry, is based on 1000 kernels randomly removed with an

electronic seed counter from the bulk grain of each harvested m^2 area.

Kernels per spike (head)

Number of kernels per spike was calculated from measurements of the grain yield, kernel weight, and number of spikes of each one m^2 area. When grain yield (GY) is expressed in grams/m^2, kernel weight (KW) in mg/kernel, and spikes (S) in number/m^2, then kernels per spike (K/S) is:

$$K/S = \frac{(GY)}{(KW) \quad (S)} \times 1000 \qquad [3]$$

Nitrogen concentration

Nitrogen concentration was measured by procedures described by Bremner (1965b). Grain protein is the product of N concentration and 5.7.

ACKNOWLEDGMENT

The authors appreciate the total soil P analyses provided by Dr. C. V. Cole, ARS, at Fort Collins, CO.

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CHAPTER 3. CLIMATIC DATA ACQUISITION

Harold R. Duke and Michael C. Blue[1]

INTRODUCTION

Scientists at Fort Collins and Akron, Colorado were given the assignment of selecting equipment and developing uniform procedures for climatic data collection. After initial equipment selection, testing, calibration and development of peripherals, the equipment was installed at seven field sites in the Central Great Plains for the 1977-78 growing season. During the first season, uniform data collection procedures and data integrity checks were developed. Based on this first year's experiences, some changes in equipment and procedures were adapted prior to expansion of the data collection system to sites in the Northern and Southern Great Plains and, in somewhat modified form, eventually to the Pacific Northwest. Nineteen site-seasons of data were collected in the Central Great Plains.

The first consideration for equipment selection was that ac electrical power was generally not feasible at the remote data stations. This eliminated from consideration several otherwise desirable sensors, particularly for humidity, and limited the choice of data loggers.

The data logger was not required to operate at high speed, with only 14 sensed pieces of data per hour required. However, because some sites were as far as 750 km from the ARS servicing location, the system had to be capable of unattended operation for periods up to two weeks. Since data were to be collected over a 10-month winter wheat growing season, the system had to be capable of storing, in computer readable form, the 150,000 pieces of data collected at each site each season. With no practical means of artificially controlling the data logger temperature, the system was required to operate reliably from about -30° to 40°C. As attention would be infrequent, it was also necessary that a means of field verification of the values of sensor output be provided. With these conditional requirements identified *a priori*, the climatic data collection system described in the paragraphs to follow was developed. As is the case with most electronic equipment, the data logger was superseded by new models soon after the project was initiated. Thus, some of the equipment may have been considered obsolete practically as soon as the project began.

FIELD INSTRUMENTS

A schematic representation of the field installation is shown in Figure 1. The various components of the data collection system are discussed in subsequent paragraphs.

Data Logger

At the initiation of this project we were aware of only two suitable data loggers available off-the-shelf. Based on its modular design, range of input signals accepted, future expandability, cost, and the fact that it was under GSA contract, we selected the Campbell Scientific CR-5[2] data logger.

This unit has a selectable sampling frequency from 5 minutes to 24 hours, with the 60-minute frequency used in this study. Each module is sampled in

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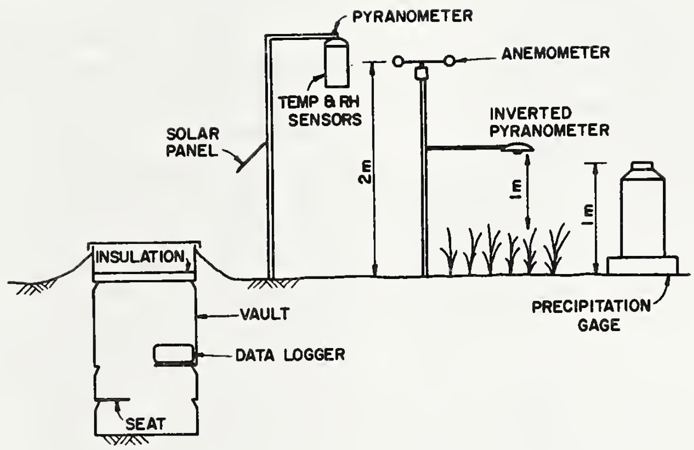

Figure 1. Schematic representation of instrument locations in the field.

order of its connection to the bus line, with a sampling cycle of 600 ms per channel. Analog input signals are averaged over a 300 ms sampling period, effectively filtering high frequency voltage spikes frequently encountered with field sensors in a harsh environment. Sensor modules have a typical input impedance of 50 Mohms which generally allows for long sensor leads with negligible resistive line loss.

Data are output to both a paper tape printer and an audio magnetic tape. Although only three significant digits are recorded, coding of the most significant digit allows a recorded range of 30 percent over full scale.

[2] Brand names are mentioned for the convenience of the reader and do not imply endorsement of specific manufacturer's products. A complete listing of manufacturers' addresses for the equipment used in this study is given in the appendix.

Modules Used. In addition to the bus line and power supply, the data loggers consisted of the following CR5 modules:

a. T102 Control - This module contains the clock, the sampling frequency switch, switches for manually initiating a data scan and clearing memory registers, and switches with which to set the minute, hour (military), and a two digit day number. This day number was used to represent the two least significant digits of the Gregorian day.

b. CR50 Printer - The impact type, electromechanical printer provides hard copy output on adding machine or fan fold paper tape, two data points per line. Each data point consists of a two digit sequential channel number, the input signal polarity, and three significant data digits.

c. A104V Four Channel Volt Range Integrator - This module provides continuous averaging of four single polarity input signals by summing a 300

ms sample for each input every 2.4 seconds and accumulating these values. Because of the method of integration used (i.e. accumulation of scaled values), a manually initiated scan results in printout of values which are related to the true integrated value by the proportion of the selected scan interval that had lapsed at the time the manual scan was initiated. Because any scan clears the accumulation registers, manually induced scans complicate interpretation of the data, and should be minimized.

Each channel has individually selectable full-scale ranges of 10, 100 and 1000 mv with a full-scale range multiplier of 10, switchable for all channels simultaneously. The switch settings used for each channel are given in Table 1. These four channels were used, respectively, to integrate incoming short wave radiation, reflected short wave radiation, and negative and positive air temperatures.

d. S210T 10 Channel Temperature Scanner - This module is a thermistor referenced copper-constantan thermocouple unit with a range of $\pm$ 99.9°C. An output terminal is connected to the amplifier output of the last channel to be scanned during the interval between scans. This output was used to provide the air temperature as an input to channels 3 and 4 of the A104V (with channel 3 at negative polarity, 4 at positive) for temperature integration. Thermocouples were used to measure soil and air temperatures and the data logger shelter temperature.

e. C102 Pulse Counter - This two channel pulse counter is capable of counting either a point closure or low-to-high voltage transition at up to 500 Hz. Divider switches for each channel allow scaling to reduce the number of counts to be stored or to convert to engineering units. Both channels were used simultaneously to record wind run.

f. P200D Power Supply Controller with Delay - This module provides a switch closure upon initiation of each data scan, and halts the scanning of modules placed after the P200D for a preselected time to allow sensor equilibration. The module was intended to serve two purposes in the current study, i.e. to provide power to high current sensors only as necessary for sampling, and to supply heating current to the matric potential sensors for a controlled period of time. The time delay setting is by a 7 bit binary switch, with least significant bit on the left. Each binary digit represents 0.1 minute (6 seconds) pause of scanning upon reaching the P200D module. The switch contacts are closed at the beginning of a scan. Thus, some calculation is needed to provide a predetermined length of point closure prior to sampling a given sensor. For example, the matric potential sensor was to be energized for 180 seconds prior to reading. These sensors were to be connected to the 24th and 25th channels of the data logger. At the scan cycle rate of 600 ms per channel, a normal scan will result in reading these two sensors 14.4 and 15.0 seconds after point closure, respectively. The remaining 165 seconds is achieved by programming a pause into the P200D prior to sampling the module that follows it. Twenty seven units (2.7 min) of delay are required and is achieved by setting bits 1 (.1 min), 2 (.2 min), 4 (.8 min) and 5 (1.6 min) "ON".

g. S210V 10 Channel Volt Sampler - This "instantaneous" sampling module gives a 300 ms average of analog inputs in the 10, 100 or 1000 mv ranges, and like the A104V has an optional full range multiplier of 10 for all chan-

CH. NO. PRINTED	MODULE NO.	CH. ON MODULE	FUNCTION	SWITCH	SWITCH POSITION	TYPICAL PRINTED OUTPUT	SENSOR (INPUT) TERMINALS VOLTS	AT TEST TERMINAL VOLTS	REMARKS
	T102 - TIME CONTROL			TIME INTERVAL	60				
00			Gregorian Day			00* 00 - 00* 99	-	-	Set with thumbwheel
01			Military Hour			01* 00 - 01* 23	-	-	switches and day, hour,
02			Minute			02* 00 - 02* 59	-	-	minute push buttons (use local Standard Time)
	A104V - VOLT INTEGRATOR			F.S. RANGE MULT.	1.0				
				OUTPUT SELECT	SCAN				
03		1	Solar radiation	Volts F.S.	.01	03*000 - 03*880	0.000 - 0.009	Do not Read	
04		2	Reflected Rad.	Volts F.S.	.01	04*000 - 04*999	0.000 - 0.010	Do not Read	
05		3	Air Temp. (-)	Volts F.S.	1.00	05*000 - 05*400	-0.500 - 0.400	Do not Read	
06		4	Air Temp. (+)	Volts F.S.	1.00	06*000 - 06*500	-0.400 - 0.500	Do not Read	
	S210T - TEMPERATURE SAMPLER			CHANNELS SCANNED	10.00				
07		1	Soil Temp. 1a			07*400 - 07*500	Do not Read	-.40 - +.50	Turn channels scanned
08		2	Soil Temp. 1b			08*400 - 08*500	Do not Read	-.40 - +.50	to number of channel
09		3	Soil Temp. 2a			09*400 - 09*500	Do not Read	-.40 - +.50	to be tested, (i.e.,
10		4	Soil Temp. 2b			10*400 - 10*500	Do not Read	-.40 - +.50	channels 1-10). Return
11		5	Soil Temp. 3a			11*400 - 11*500	Do not Read	-.40 - +.50	to 10 when finished.
12		6	Soil Temp. 3b			12*400 - 12*500	Do not Read	-.40 - +.50	
13		7	Air Temp.			13*400 - 13*500	Do not Read	-.40 - +.50	
14		8	Canopy Temp.			14*400 - 14*500	Do not Read	-.40 - +.50	
15		9	Shelter Temp.			15*400 - 15*500	Do not Read	-.40 - +.50	
16		10	Air Temp.(Dup. CH 13)			16*400 - 16*500	Do not Read	-.40 - +.50	
	R235 - AUDIO TAPE INTERFACE			MEMORY UNLOAD	AUTO RESET	(INDICATED BY TAPE ADVANCE)	SWITCH MEMORY UNLOAD TO "UNLOAD" AT LEAST TWICE BEFORE REMOVING TAPE.		
	C102 - PULSE COUNTER								
17		1	Wind Run	Divider	100000	17*000 - 17*:99	Voltage Pulse		Divider switches: "0"
18		2	Wind Run(dupl.)	Divider	100000	18*000 - 18*:99	each 1/10 mile		refers to open position
	P200D-POWER SUPPLY TIME DELAY			DELAY	1204500				Delay setting 1204500 used with soil moisture. (165 sec. delay). Use 0200000 until soil moisture sensors installed.
	S 210V - VOLT SAMPLER			F.S. RANGE MULT.	10.0				
				CHANNELS SCANNED	10				
19		1	Rain Gage Battery	Volt. FS	0.1	19*-99 - 19*:99	1.1 - 1.3	Do not Read	
20		2	Rain Gage Output	Volt. FS		20*000 - 20*:99	1.1 - 1.3	Do not Read	
21		3	WM Input	Volt. FS	1.0	21*340 - 21*380	3.6 ± 0.2	Do not Read	
22		4	WM Output	Volt. FS	0.1	22*000 - 22*500	0.0 ± 0.5	Do not Read	
23		5	Hair Element Out	Volt. FS	1.0	23-999 - 23*999	-10.0 - 10.0	Do not Read	
24		6	Soil Moist. 1	Volt. FS	1.0	24*000 - 24*200	0.0 - 2.0	Do not Read	
25		7	Soil Moist. 2	Volt. FS	1.0	25*000 - 25*200	0.0 - 2.0	Do not Read	
26		8	CR5 Battery	Volt. FS	1.0	26*999 - 26* 99	11.0 - 15.0	Do not Read	
27		9	-Short-	Volt. FS	1.0	27*000		Do not Read	
28		10	-Short-	Volt. FS	1.0	28*000		Do not Read	

Table 1. Data logger configuration.

nels. This module was used to record analog outputs from the precipitation gauge, humidity and soil moisture sensors and batteries for the precipitation gauge and the main system, with unused inputs shorted.

h. R235 Cassette Interface Module - The cassette interface module provides a means of recording data in computer compatible form with audio quality cassette tape and recorder. This unit has a 70 channel buffer to allow storage of several 10 channel lines of data in memory prior to dumping to the recorder. Data handling is controlled by an on-board microprocessor. A front panel switch allows dumping of partially filled buffers before changing tapes so that all data from a single scan appear on a single data tape. Data are transmitted to tape in standard ASCII format, but as a series of voltage pulses rather than the tones usually associated with audio recording. A companion unit, the A235, is used to convert this audio tape output to standard RS232 signals for input to the office computer.

j. Audio Cassette Recorder - A moderately priced audio cassette recorder is used to collect data in computer compatible form. These recorders are modified to provide control via the "REMOTE" switch of the amplifier circuits as well as the tape drive motor, so that the machine may be left in "RECORD" mode for extended periods without undue battery drain. The built in microphone was disconnected to prevent recording of voice or extraneous noise when servicing the equipment with cables unplugged.

Problems Encountered. Inconsistent head alignment between the several machines used to record data and the few used to transcribe data was a serious problem, as tapes generated on one recorder sometimes could not be read on another. The recorders used have a screw for adjustment of head alignment, accessible on most models only after removal of the case half nearest the recording head. At the data logger manufacturer's suggestion, a test tape was prepared which consisted of a continuous series of character "U" (ASCII character 55 Hex). This character string results in a series of uniformly spaced pulses, which can be monitored with an oscilloscope attached to the "Monitor" jack. Adjustment of the heads in all machines to give maximum pulse amplitude matches the head alignment to that of the machine on which the test tape was recorded.

When the first data logger units were received, the manufacturer had applied moisture sealer by dipping the printed circuit boards.For several weeks afterward, sealant that had seeped into IC sockets apparently swelled on drying, effectively insulating IC's from their socket. Eventually, all machines were returned to the factory for complete solvent cleaning. Subsequent sealing was done using spray techniques rather than dipping, with no further problem. Perhaps three quarters of the data logger failures were traceable to problems of electrical continuity through connectors. As a matter of routine, a policy was established to clean the bus line connectors with a ruby eraser whenever the machine was disassembled for any reason. This routine cleaning significantly reduced the incidence of data logger failure and has not resulted in visible damage to the gold plating on the contacts.

Particularly the first season, when the unit was sheltered above ground, low ambient temperatures resulted in very sluggish operation of the paper tape printer and audio tape recorders. This

problem all but disappeared in subsequent years when shelter temperature seldom went below freezing.

During periods of high humidity, the paper tape absorbed water to the extent that the fan fold paper would not feed through the printer. We solved the problem by fabricating a DC motor driven take-up spool to utilize adding machine tape. This takeup spool was provided with a friction disk slip clutch, and was powered only during a data scan through the contacts of the P200D unit. This takeup mechanism is currently available from Campbell Scientific.

The only other problem of any frequency was that most machines would occasionally fail to record the last channel of data in a scan. This problem was never corrected, but we were able to assemble the modules in such order that the last module had at least one unneeded data channel. The machine was thus set to record one channel beyond the required data so that no data were lost whenever the last channel was not recorded.

Power Supply

The manufacturer suggests 4 to 6 months operation on eight internally mounted alkaline "D" cells. However, with the number of channels scanned (28), the frequency of scanning (hourly) and the fact that we operated both the humidity sensor and the paper takeup motor from the data logger power supply, internal batteries were found to provide reliable operation for only about three weeks. An external, rechargeable 12 volt gelled electrolyte lead-acid battery of 4.5 amp-hour capacity proved satisfactory throughout the project. A 32 element photovoltaic panel, rated 14 volts, 1.5 watt peak output, was used to retain the batteries at full charge. The potential user should note that the commonly available nickel-cadmium battery is quickly destroyed by such a charging scheme which retains the batteries at virtually full charge. Because the solar panel is connected to the battery continuously and provides a conductive path during periods of low radiation, a blocking diode must be installed to prevent discharge of the battery through the solar panel during the night. The panel surface had to be cleaned regularly to keep it reasonably free of bird excrement and several panels were damaged when birds pecked through the transparent silicone rubber covering and damaged the interelement connections. This damage was readily repaired by resoldering and coating the surface with RTV silicone rubber.

This nominal 12 volt power supply was also used as input to a 3.6 volt zener regulator to power the Vaisala humidity sensor the first season, and to a ± 15 volt DC to DC converter used to provide 30 volts excitation to the LVDT humidity sensor in subsequent years. To conserve power, this 12 volt supply was switched to the sensors only during a data scan (i.e. hourly).

Temperature Sensors

All temperatures were sensed with copper/constantan thermocouples. With the exception of leaf thermocouples, all were fabricated using 24 AWG ANSI type T duplex polyvinyl insulated thermocouple wire. The junction was formed by stripping approximately 1 cm of both conductors, twisting tightly 1 1/2 turns and soft soldering the junction. The junction was then insulated with RTV silicone rubber. The oscillator in the DC-DC converter used to power the humidity sensor caused spurious readings of the various thermocouples.

This interference required grounding of all thermocouple junctions by connecting a single conductor successively to each of the junctions. This conductor was then bonded to an earth ground rod near the data logger and to chassis ground of the data logger. This external ground rod reduced the likelihood of voltage spikes, as from lightning, being conducted through the data logger.

The polyvinyl insulation of this thermocouple wire deteriorated over the season, became brittle and could not be used more than one season. Hares were observed eating the insulation from the wires on several occasions, allowing the wires to touch, thus forming additional thermocouple junctions.

Air Temperature. Air temperatures were measured at 2m above the soil surface. Since ac electrical power was not available, a naturally aspirated radiation shield was necessary. A modified flat plate shield was utilized when the systems were first installed in the field. These shields provided marginal shielding at sunrise and sunset, and did not provide sufficient room for the humidity sensor we eventually used. During every snow storm, snow compacted between the plates, and with unattended operation and effective shielding from radiation, often remained for as much as a week, negating both temperature and humidity readings.

The cylindrical radiation shield shown in Figure 2 was fabricated to shield both the air temperature thermocouples and the humidity sensor. This shield, fabricated of PVC pipe and pipe fittings, is relatively easily built, with the angled ventilation slots being cut on a table saw with a carbide tipped blade. The shield itself is removable by loosening three screws, providing easy access to the sensors. A 20 mm hole in the bottom plate allows a standard Weather Bureau mercury in glass thermometer, fitted into a rubber stopper, to be inserted within the inner shield to check the thermocouple readings. Temperature readings within the cylindrical shield were compared with those within a Cotton Region shelter in a location protected from wind movement. Hourly temperatures recorded within the cylindrical shield were

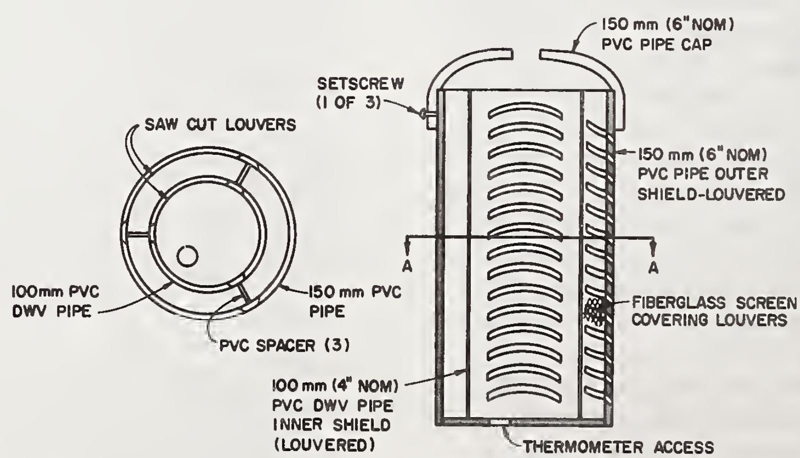

Figure 2. Radiation shield for temperature and relative humidity sensors.

within ± 2°C of those at the center of the Cotton Region shelter. Temperatures measured in a vertical profile within the Cotton Region shelter varied from that at the center by a similar amount. It is important to note that the radiation shield and sensors must be insulated from earth ground (PVC pipe connector in Figure 2). The DC-DC converter used to power the humidity sensor provides ± 15 VDC as required for the soil moisture sensors. This converter is used to supply 30 VDC to the humidity sensor, connecting the -15 volt supply to the sensor common. Thus, the humidity sensor low input is not at the same potential as the data logger chassis ground.

As an aid in estimating maxima and minima, and because two integrator channels were available, the air temperature was integrated to give the average temperature each hour. The S210T module was connected such that the last channel sampled (10) recorded air temperature. The output of the last channel sampled appears at the "TEST" terminal of the S210T. Thus, this terminal was connected to terminals 3 and 4 of the A104V integrator. Because only signals of positive polarity are integrated, two channels of the integrator are required when subfreezing temperatures may be encountered, having the input polarity reversed on one channel. Methods of estimating maxima and minima are described in Chapter 4.

Soil Temperature. Soil temperatures were measured at three locations at each site, two depths per location (3 and 5 cm). Thermocouple wires as long as 500 m were utilized. Since the thermocouples were buried at very shallow depths, the soil cover provides little physical resistance to thermocouple disturbance; therefore a stiff wire hoop was provided near each pair of junctions to secure the wire.

Canopy Temperature. Estimates of canopy temperature were made by two different techniques. During the first season, a naturally aspirated radiation shield, fabricated from short lengths of white PVC pipe, was used. This shield consisted of a 10 cm long section of 25 mm pipe, inside of which the thermocouple was mounted. A semi-cylindrical section of 38 mm pipe was mounted above the 25 mm section, with an air gap between. This assembly was mounted on a steel stake in such a manner that the shield could be adjusted to the height of the crop canopy and oriented in the direction of the prevailing wind.

In subsequent years this system was abandoned in favor of a thermocouple attached directly to the underside of a leaf. This thermocouple was fabricated from varnished 36 gauge copper and constantan wires approximately 15 cm long. These fine wires were soldered respectively to the copper and constantan conductors of the 24 gauge type T wire for mechanical strength. The thermocouple junction was attached to the underside of a leaf near the top of the canopy with transparent tape.

Wind

Air movement (2 m height) was recorded as total wind run during the sampling interval. Because the input impedance of the counting module is very high (50 Mohm) the current through the switch contacts is very low, and contact contamination became a critical problem. Because it has high quality, hermetically sealed contacts, Campbell Scientific suggested the Cassela anemometer for use with this system. A sample, however proved to have very heavy cups

and a higher threshold velocity than the Belfort anemometer. For this reason (and their availability through GSA contract) the Belfort 5-349 was chosen for these systems.

As predicted, contact contamination soon created problems with the data logger failing to register a count every time the contacts closed. The first effort at correction was to gold plate those contacts for reduced electrical resistance. Plating resulted in some improvement, but the problem remained. A feasible solution was achieved by replacing the switch cam with a small magnet and the exposed contacts with a hermetically sealed reed switch. This conversion reduced the resolution from one pulse every 27 m (1/60 mi.) to one pulse every 160 m (1/10 mi.).

The pulse counter module (C102) has three terminals for each input channel. The sensor may be connected either of two ways, with the sensor contacts between + and IN terminals or between IN and GROUND terminals, with a shunt resistor from the IN to the unused terminal. However, the + terminal goes to ground during a scan. Since a count is registered on the low to high transition at the IN terminal, shunting + to IN results in one extra count registered each time the machine scans. Thus, for accuracy of counting, a 2.2 Mohm resistor was connected between ground and IN, with the sensor contacts from + to IN.

Precipitation

Because no practical means was available for gauge heating, the otherwise desirable tipping bucket gauge was not considered. Rather, the Belfort transmitting gauge (6089-12) was utilized to provide an analog input to the data logger. The collector of this gauge was mounted 1m above ground. The gauge was winterized with $CaCl_3$ solution and evaporation suppressed with 20W motor oil. To avoid running regulated bus voltages externally to the data logger, a separate battery was utilized to provide excitation of the rain gauge potentiometer. The data logger recorded both input and output voltage from the gauge. A single AA size alkaline battery was mounted in series with the 25 Kohm raingage potentiometer and a 4.7 Kohm dropping resistor. This dropping resistor was necessary to reduce the 1.5V nominal battery voltage to 1.3 volts to maintain the potentiometer voltage within the recording range of the data logger. With current levels in the picoampere range, battery life is virtually shelf life, thus batteries were only changed once each season. The high input impedance of the data logger (50 Mohm) resulted in virtually linear output of the raingage with respect to accumulated precipitation.

This sensor was the most trouble free of all those utilized on this project. Each was calibrated prior to each season ($r^2 = 0.999$), and checked with a standard weight (equivalent to 25.4 mm) each time the ARS technician visited the site.

Incoming Solar Radiation

Incoming shortwave radiation was measured using the Licor pyranometer, model 2200, with millivolt adapter (100.0 ohm shunt resistor), mounted atop the radiation shield at approximately 2m above the soil surface. Minor problems were experienced with maintaining the sensor level and removing bird excrement. These sensors were recalibrated annually against an Eppley black and white pyranometer, with at least one

mid-season check in the field. Decrease in pyranometer sensitivity averaged 3.3 percent per season.

Reflected Radiation

Reflected short term radiation was measured with a Spectral Associates pyranometer, mounted in an inverted position. The pyranometer has temperature compensation in the base, which required shielding of the pyranometer itself from radiation. A shield was fabricated from a chrome plated "moon" automotive hubcap, lined with 12 mm foam plastic. A mounting bracket was attached to the hubcap such that a full hemispherical view was assured.

These sensors proved unsatisfactory, and all failed before the end of the data collection period. Other locations participating in this study have not experienced such poor service from these instruments, however.

Humidity

The water content of the air is the most difficult climatic parameter to measure of all those of interest in this project. Conventional primary and secondary humidity sensors, such as optical and conductive salt devices, were eliminated because of the lack of ac electrical power and the need for frequent operator attention. Wet bulb devices were deemed inappropriate because of frequent anticipated subfreezing temperatures.

During the first season, two types of sensors were used. The first, a bulk effect transducer (Brady array) was advertised as providing very accurate readings with fast response. The sensor was calibrated in the laboratory over standard saturated salt solutions, and appeared to give reasonable results. Likewise, field readings initially corresponded well with those obtained with a sling psychrometer. By midseason, however, it became obvious that readings from the Brady array bore little resemblance to those from the sling psychrometer. The sensor was subsequently returned to the laboratory and a steady state calibration run in a controlled environment chamber using an optical dewpoint hygrometer as a standard. This calibration showed a scatter of data in the mid-ranges of humidity in the order of 40 percent relative humidity. This sensor was thus dismissed as unuseable for this project.

The second sensor evaluated was the polymer thin film capacitor type manufactured in Finland by Vaisala and marketed in the U.S. by Weather Measure. When first installed, these sensors had only a screen around the sensing element to protect it from contamination. The sensors appeared to work properly immediately after installation, but deteriorated quite rapidly. In as little as two weeks, the output was meaningless. Replacement of the sensor element requires complete recalibration. Subsequently, a sintered bronze filter, available from the supplier, was installed, but made no noticeable difference in sensor life. Although the fact that the sensors were powered only for a few seconds each hour may have contributed to their unsatisfactory service, similar experiences were cited by McKay (1978).

With these two low power input sensors providing unsatisfactory service and no others available at that time providing any more promise, we began designing our own sensor. Having had relatively satisfactory service from the conventional hair element humidity sensor as used in the hygrothermograph, this element was used as a basis for an elec-

tronic sensor. Figure 3 illustrates how a hygrothermograph hair element was connected, through a mechanical linkage, to move the ferrous core of a linear variable differential transformer (LVDT) to provide a DC output voltage proportional to relative humidity. This sensor has provided satisfactory service, with a standard deviation on relative humidity of approximately 0.7 percent RH at a given temperature. The sensors are somewhat temperature dependent, with a typical calibration equation:

$$RH(\%) = 53.0 - 7.00V + .293V^2 - .0035T$$

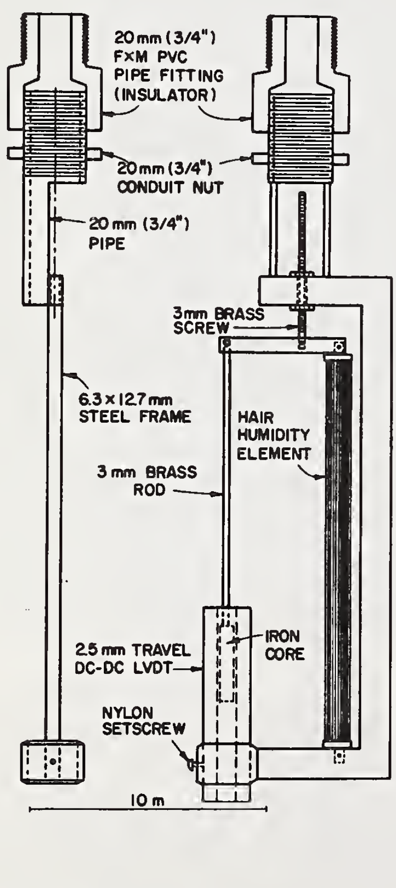

Figure 3. Hair humidity sensor developed for study.

where V is output voltage at 30.0VDC input and T is Kelvin temperature. Typical r^2 values exceeded 0.97.

This sensor was used subsequently for all humidity measurements. All sensors were recalibrated prior to each data collection season. Few problems were encountered with the sensor other than failure of two or three LVDT's, and a shift in calibration associated with movement of the LVDT core or coil, primarily during transport.

Soil Water

At the outset, it was intended that soil water content be measured at two depths at each site using the new matric potential sensor available from Moisture Control Systems, Inc. This sensor, based on the dependence of thermal conductivity in a fixed porous body on its water content, requires that a regulated current be dissipated through the sensor heater for a controlled amount of time. After that time, the temperature at a fixed sensor is dependent on the water content of the ceramic matric. Thus, the P200D time delay module was required to control the energization of the sensor via the $\pm$15V DC to DC converter. Manufacturing problems delayed delivery of the first two sensors for almost two years. Those sensors gave an output that could not be correlated with soil moisture. Thus, these sensors and the plan to measure soil moisture at all sites were abandoned.

Data Logger Shelter

During the first season of operation, the data loggers were housed in a small above ground shelter (approximately 75 x 75 x 50 cm) fabricated of plywood with 5 cm of fiberglass insulation.

The shelter was mounted on 20 x 20 x 40 cm concrete blocks, i.e. supported 20 cm above the ground. With little mass internally to retain heat, the temperature inside the shelter fluctuated virtually the same as the ambient air temperature, reaching -23.8°C with the coldest ambient temperature of -28.0°C at that site and rising to 33.4°C when the ambient rose to 35.8°C. As a result, the operation of the mechanical printer slowed to a virtual stop during extremely cold weather.

More critical than data logger operation, however, was the inability of the operator to service the data system while exposed to the wind and cold. During the course of data collection, temperatures as low as -29.6°C were recorded. With the wind frequently accompanying low temperatures in the Great Plains, it was virtually impossible for the operator to adjust and maintain the data logger barehanded.

After the first year, the data logger was sheltered below ground. A fiberglass electrical transformer vault (.9m diameter, 1.7m high) was buried in a vertical position, with the top 30 cm extending above the soil surface. A removable plywood plug with 5 cm thick plastic foam insulation was fitted inside the vault, just below ground level. A waterproof top was fitted with a transparent acrylic window to admit daylight into the vault when servicing. A shelf for the data logger, seat and ladder provided easy access for the attendant, and allowed him to sit inside with the top door closed to service the data logger. This shelter provided considerable moderation of the temperature of the data logger, resulting in much improved operation of the printer and tape recorder. During the coldest days of the season, the shelter temperature averaged 0.7°C, 19.4° above the ambient temperature. Summer temperatures were moderated to a lesser extent, with the average maximum shelter temperature 4.4°C below the average maximum ambient. Most important, the vault provided shelter for the operator to effectively service the data logger when required.

With an open bottom as originally installed, moisture from the soil below condensed on the data logger, resulting in potential damage. Fitting a plywood floor to the vault, sealed in place with silicone rubber caulking, eliminated the condensation problem.

DATA COLLECTION

The anticipated volume of data to be assembled was potentially overwhelming, with up to 60 season years of data to be collected, representing some 8 million pieces of data. With that data volume, the surety that some data would be missed, and the myriad of people handling the data at various positions along the path of data collection, it became obvious that very detailed, even redundant, record keeping was necessary. Such detail should improve data quality and provide benchmarks at reasonable time intervals at which automatically logged data could be compared with manually collected data.

Data Logger Setup

To insure consistency between locations and observers, Table 1 was prepared on a Mylar sheet and attached inside the lid of each data logger to insure its availability. This table shows the order of module installation, the function recorded in each data channel and the required position of each switch on each module. This information was particularly helpful whenever sensors were

disconnected to replace a defective module. With some forty leads connecting to the data logger, the importance of a consistent color coding scheme and method of labeling sensor leads becomes obvious.

The information in Table 1 serves another important function for the observer, in that it indicates the expected range of both printed and analog values at input and output terminals, and helps to detect equipment malfunctions.

System Servicing

The minimum frequency of system service was dictated by the length of recording media available. High quality 60 minute audio cassette tapes were selected for the magnetic recording medium, as the thinner tape of longer cassettes has a tendency toward stretching and inconsistent speed due to slippage. These 60-minute tapes have capacity for 18 to 19 days' data as used on this system. The paper tape rolls, after trimming to fit under the take-up device, have a larger capacity but will not reliably hold 4 weeks' data. Cassette tapes, paper tape and cassette batteries were changed at 14-day intervals to assure reliable operation and reserve capacity when extreme weather conditions precluded service.

During the first season of operation, the seven initially installed stations were serviced by technicians from Fort Collins (3) and Akron (4), Colorado at two week intervals. To expedite repair of the data loggers, a complete spare unit was acquired for each of the technicians, so that modules could be replaced without making two trips. Station servicing required 40 to 50 percent of each technicians' time, requiring about 1500 km each trip, and it became apparent that two week intervals between service were inadequate to maintain the desired quality of data.

During subsequent seasons, contractual arrangements were made with local observers to provide, for a modest fee, service at least twice weekly at each station. These observers ranged from science oriented high school teachers and experiment station personnel to a cooperating farmer. In most instances, this arrangement was very satisfactory, greatly improved the quality of data, and problems were detected much sooner. Each observer was provided a kit of supplies, including a digital multimeter with LCD display. Because these observers were not trained technicians, a very detailed data sheet was provided (Figure 4). This data sheet provided for both qualitative and quantitative observations and for redundancy in several data. Instantaneous data were recorded both as printed and as measured with the multimeter. The observer was required to calculate the variable values in engineering units and compare values. Allowable differences are shown for each parameter. The apparently large allowable differences for channels 3-6 and 22-23 are due respectively to the fact that the printed values of the former are integrated values scaled by the 60-minute sampling interval and that the humidity sensors can be expected to have significant response time to changes in humidity.

These data sheets were printed in self-carboned triplicates and bound into a notebook. On completing an observation, the observer followed the checklist on the third sheet, then mailed two copies of the data sheet to the appropriate technician. One copy remained in the technician's service file, the other accompanied the data. Whenever malfunctions were detected,

CR5 OBSERVER'S LOG

I. Date:______________________ Station:______________________
Gregorian Day:______________
Local Standard Time:__________ Observer:______________________

II. WEATHER SUMMARY DURING PAST WEEK

Day	Date	Cloud Cover			Temperature			Humidity		Wind			Precipitation
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.
		Clr	Pc	Cldy	C	Mod	W	Hi	Lo	Lo	Mod	Hi	In.

III. OBSERVED SITE CONDITIONS

Soil Surface: Dry Wet

Wheat Height:______________Inches

Plant Color:_________________________
Other observations (winterkill, grazing, insects, dormancy, spring growth, etc.)

IV. MANUALLY COLLECTED DATA

Anemometer Reading__________.____Miles

Psychrometer: Wet Bulb __________ °C

Air Temperature_______________°C

Dry Bulb __________ °C

Rel. Humidity______%
(from chart)

V. DATA ACQUISITION SYSTEM

1. Time of last printout 00*____ ____ 01*____ ____ 02*____ ____
2. Press SCAN button on T102
3. Read and record input voltages to channels 21 through 25
4. Time of printout 00*____ ____ 01*____ ____ 02*____ ____
5. T = Min. (Time between two preceeding printouts)
6. Record Local <u>Standard</u> Time from wristwatch__________________________
   If 6 differs from 4, more than 30 minutes, correct as per instructions.

Figure 4. Observer's Data Sheet

CHANNEL NO.	PARAMETER	VOLT METER READING	PRINTED OUTPUT	CALCULATED VALUE (Col. 3)	ALLOWABLE DIFFERENCE
-- T102 --					
00	Gregorian Day			Time from watch	
01	Military Hour			in "VM Reading"	
02	Minute			Column	30 minutes
-- A104V --					
03	Solar Radiation	______ MV	___ . ___ ___	______ LY/M	± 50%
04	Reflected Rad.	______ MV	___ . ___ ___	______ LY/M	± 50%
05	Air Temp. (-)	______ V	. ___ ___ ___	______ °C	± 10°C
06	Air Temp. (+)	______ V	. ___ ___ ___	______ °C	± 10°C
--S210T--					
07	Soil Temp. 1a	______ V	. ___ ___ ___	______ °C	± 1°C
08	Soil Temp. 1b	______ V	. ___ ___ ___	______ °C	± 1°C
09	Soil Temp. 2a	______ V	. ___ ___ ___	______ °C	± 1°C
10	Soil Temp. 2b	______ V	. ___ ___ ___	______ °C	± 1°C
11	Soil Temp. 3a	______ V	. ___ ___ ___	______ °C	± 1°C
12	Soil Temp. 3b	______ V	. ___ ___ ___	______ °C	± 1°C
13	Air Temp.	______ V	. ___ ___ ___	______ °C	± 1°C
14	Soil Temp. 2	______ V	. ___ ___ ___	______ °C	± 1°C
15	Shelter Temp.	______ V	. ___ ___ ___	______ °C	± 1°C
16	Air Temp (Dupl 13)	______ V	. ___ ___ ___	______ °C	± 1°C
--C102--					
17	Wind Run	______ CNT	___ ___ . ___	______ M/H	
18	Wind Run (Dupl)	______ CNT	___ ___ . ___	______ M/H	
--S210V--					
19	Rain Gage Batt	______ V	. ___ ___ ___	______	1.1V
20	Rain Gage Output	______ V	. ___ ___ ___	______ In.	± .010V
21	WM Humidity Input	______ V	___ . ___ ___	______	3.6 V ± 0.2V
22	WM Humidity Output	______ V	. ___ ___ ___	______ %	± 10% RH
23	Hair Humidity Output	______ V	___ . ___ ___	______ %	± 10% RH
24	Soil Moisture 1	______ V	___ . ___ ___	______ bar	± .2 bar
25	Soil Moisture 2	______ V	___ . ___ ___	______ bar	± .2 bar
26	CR5 Battery	______ V	___ . ___ ___	______	13.0 ± 2.0V
27	Not Used				
28	Not Used				

Figure 4. (Continued)

VI. SYSTEM SERVICE

1. Switch to "UNLOAD." ______
2. Record tape counter. ______
3. Rewind 5 counts and check for recorded data. ______
4. Return to original count plus 1, replace "REMOTE" cable, place in "RECORD" mode.
5. CRS battery charge current ______________ M. A. (check if 11.0V)
6. CR5 battery replaced? ______________
7. Raingage emptied? ______________ Volume removed ______________ ML.
   820 ml = 1 inch
8. Time to change tapes? ______________ (2 week intervals)
   a. Remove and label cassette ______
   b. Replace cassette batteries ______
   c. Label and install new cassette ______
   d. Remove, label, and replace paper tape ______
9. Replace all switches in operating position ______
10. Place tape recorder in "RECORD" mode.
11. Secure case lid ______

VII. ARS PERSONNEL ONLY

1. Check raingage calibration

   CH 19 ______________ V　　CH 20 with weight ______________ V

   CH 20 without weight ______________ V　　V (CH 20) ______________ V

   V CH 19 = ______________ (Approx. 0.07)

2. Check raingage level ______________

3. Check pyranometer level ______________

4. Instruments/sensors changed (change tape if sensors changed)

Instrument	S. No. Removed	S. No. Installed

VIII. Note Data Problems and Corrective Action Taken:

Figure 4. (Continued)

either by the technician or observer, an attempt to correct the problem was made by direct telephone contact before the technician drove to the site.

LITERATURE CITED

World Meteorological Organization 1970. Guide to hydrometeorological practices. WMO-No. 168.TP.82, Geneva, Switzerland.

D. J. McKay. 1978. A sad look at commercial humidity sensors for meteorological applications. Fourth Symp. on Meteorological Obs. and Instr., Amer. Meteorological Society, Denver, CO. p. 7-14.

APPENDIX

SOURCES OF EQUIPMENT

Campbell Scientific, Inc. P.O. Box 551 Logan, UT 84321	(CR5 Data Logger)
Power Sonic Corp. Redwood City, CA	(Gelled electrolyte battery)
Solarex Corp. 1335 Piccard Dr. Rockville, MD 20850	(Solar battery charger)
Thunder Scientific 623 Wyoming SE Albuquerque, NM 87123	(Brady array humidity sensor)
Weather Measure P. O. Box 41257 Sacramento, CA 95841	(Polymer thin film capacitor humidity sensor)
Semi Conductor Circuits, Inc. 218 River Street Hoverhill, MA 01830	(Regulated DC-DC converter)
Schaevitz Engineering US Route 130 & Union Ave. Pennsauken, NJ 08110	(DC-DC linear variable differential transformer)
Li-Cor, Inc. P.O. Box 4425 Lincoln, NE 68504	(Pyranometer)
Mesa Fiber Glass Co. 6471 E. 49th Drive Commerce City, CO 80022	(Fiberglass transformer vault)
Belfort Instrument Co. 1600 S. Clinton St. Baltimore, MD 21224	(Anemometer, precipitation gauge, hair humidity element)
Spectran Instruments P.O. Box 891 LaHabra, CA 90631	(Pyranometer for reflected short wave radiation)
Moisture Control Systems, Inc. 402 Walnut St. Findlay, OH 45840	(Soil moisture sensors)

245

CHAPTER 4. PROCESSING OF METEOROLOGICAL DATA FROM FIELD SITES IN THE CENTRAL GREAT PLAINS

Dale F. Heermann, Paul F. Williams and Kristine M. Stahl[1]

INTRODUCTION

The previous chapter described the equipment used for acquiring the meteorological data from the field sites. The objective was to obtain hourly data from each of the field sites for use in the testing and verification of wheat yield models. The meteorological data for the Central Great Plains wheat yield sites were collected at Akron, CO; Albin, WY; Garden City, KS; Mankato, KS; Medford, OK; Paxton, NE; and Tribune, KS. (The site names chosen reflected the closest city to the actual site.) Data were collected for three winter wheat growing seasons. The weather stations described in the previous chapter were placed in the field a few days after planting and removed a few days before harvest each year. Data were collected at all seven sites in 1977-78 and 1978-79. In 1979-80, Medford, OK, and Mankato, KS were not recorded because of funding and travel restrictions. Garden City, KS, was terminated in the early spring of 1979 due to crop failure. Therefore, there are a total of 18 complete crop-year files from the Central Great Plains to use for wheat yield model testing.

DATA PROCESSING

Precipitation, air temperature, crop canopy temperature, humidity, soil radiation, reflected radiation, soil temperature, and wind run were measured with automatic weather stations located in large wheat fields (at least 40 acres). Soil temperatures were measured at three locations and two depths. Only the average temperature at each depth was archived. The humidity data were converted to vapor pressure. Table 1 summarizes the site years which have either estimated or complete observed data. Each data file tabulated the 24-hourly observations and a daily summary value for each parameter. The daily summary values included maximum and minimum air temperature, maximum and minimum crop canopy temperature, average vapor pressure, total precipitation, average soil temperature at 1 and 3 cm depth, total reflected radiation, total solar radiation, and total wind run. The minute of the day at which observations were made were recorded as part of the header record for each data file.

The raw data collected with the field recorders were checked for errors and missing data. The data were processed in four stages. The first stage was to locate erroneous data in the scans produced by the CR5 data logger by visual examination of printed and plotted data. Plotting showed individual out-of-range values very clearly. For example, sudden spikes in the plots of individual parameters could be an indication of trouble. Also since humidity and air temperature have an inverse relationship, deviations from this pattern flagged problems. Errors in the wind run occurred with corroding contacts in the anemometer and were detected by comparing the proportional decrease in wind run with that observed from the field anemometer readings at the time of site visits. Also, individual incorrect or missing values were estimated by linear interpolation if the bad or missing value was bracketed by good data and the data did not vary too wildly.

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Table 1. Data collected on each file.

Site	Years	Days of Year Collected	Prec	Wind	Air Temp	Vap Press	Soil Temp	Solar Rad	Refl Rad	Crop Canopy Temp
		Start--End								
Akron, CO	1977-1978	286--185	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	1978-1979	276--190	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	1979-1980	305--186	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Albin, WY	1977-1978	277--194	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	1978-1979	279--200	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	1979-1980	268--191	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Garden City, KS	1977-1978	293--176	Yes	Yes	Yes	Yes	Yes	Yes	No	No
	1978-1979*	291-- 73	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	1979-1980	292--181	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Mankato, KS	1977-1978	291--186	Yes	Yes	Yes	No	Yes	Yes	No	No
	1978-1979	292--181	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Medford, OK	1977-1978	292--164	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	1978-1979	334--169	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Paxton, NE	1977-1978	278--187	Yes	Yes	Yes	No	Yes	Yes	No	No
	1978-1979	290--192	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
	1979-1980	282--180	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tribune, KS	1977-1978	271--183	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	1978-1979	290--177	Yes	Yes	Yes	Yes	Yes	Yes	No	No
	1979-1980	291--162	Yes	Yes	Yes	Yes	Yes	Yes	No	No

* Terminated early due to crop failure.

Failure of the CR5 clock (automatic data acquisition system) to keep correct time was also detected in the first stage. The CR5 data systems were serviced at two week intervals and on occasion there was a discrepancy between the CR5 clock and actual elapsed time. To correct this discrepancy the time was shifted proportionally for each scan based on the ratio of elapsed time to CR5 time.

During the second stage of processing, the data were converted to physical units and 24-hourly values were established for each day. Interpolations became necessary when either the clock speed had been in error or the scan was not at the same minute for the entire 24-hour period. Even though the CR5 automatically scanned every 60 minutes, the minute of scans changed when power was interrupted for servicing. The 24 equally spaced readings were obtained by shifting, combining and interpolating between scans. During this processing, daily maximum and minimum air temperatures for each day were calculated using integrated air temperatures in conjunction with the hourly readings. The integrated air temperature was used to determine if the temperature during the past hour was above or below the current and previous instantaneous air temperature.

The midpoint temperature was calculated by

$$T_m = 2\,\overline{T} - \frac{T_{i-1} + T_i}{2}$$

where T is the hourly integrated average temperature, T_{i-1} is the previous hours instantaneous air temperature and T_i is the current instantaneous air temperature. This relation assumes that T_m is at the midpoint of time and that the temperature transition from T_{i-1} to T_m to T_i is linear.

Precipitation was measured with transmitting weighing rain gauges. Noise in the data system was confounded with actual precipitation readings. Precipitation values that were clearly caused by noise were deleted from the record. This was an admittedly subjective process. In addition, whenever an hourly value for any parameter was not available or was in error, the missing data code was inserted.

The third stage of data estimation involved estimating sequential hourly data that were missing. If sequential values were missing yet were surrounded by good data, then the missing values were estimated by linear interpolation. A flag was set to indicate that an hourly value had been estimated. The actual number of sequential missing hours estimated by interpolation was related to the variability of the data.

The final stage provided a daily summary value for air temperature, soil temperature, solar radiation, and precipitation for each day in the data set. If all 24 hourly readings were present, then the daily summary value was the appropriate composite of those values. If any of the missing 24 hourly readings were not estimated, then selected daily summary values for temperature, precipitation, and solar radiation were estimated independently. The daily summary estimates for air temperature, precipitation, and solar radiation were based on weather data published by the National Oceanic and Atmospheric Administration (1976-1980). Soil temperatures were estimated from the air temperature data. The estimation procedures are given in later sections.

The Akron data were estimated from an alternate set of daily data collected at the Akron field station. The soil temperatures were estimated by the same

procedure used at the other sites.

The hourly and daily summary data were coded so that missing and estimated values were marked. Each of the hourly values was marked to show whether it was originally present or missing. (Out-of-range values were treated as missing.) The daily summary codes indicate if the summary was missing, if the summary was computed from the hourly values or estimated by an independent technique. The independent techniques for air temperature, soil temperature, precipitation and solar radiation are described below.

Air Temperature Estimation

Air temperatures were estimated using a method similar to that suggested by Landsburg (1966). Three NOAA weather stations surrounding each of the seven field sites were selected. It was necessary to adjust the dates for some of the stations because the field data for each day were tabulated at midnight; whereas the NOAA data were tabulated at either 8 a.m. or 6 p.m. The minimum temperature usually occurred in the early morning and the maximum in the midafternoon. This time pattern meant that NOAA data collected at 6 p.m. would correspond to the field data, whereas data collected at 8 a.m. would contain the previous day's maximum temperature. The maximum temperature for these stations was shifted to the previous day.

Using the NOAA data and the valid measured field site data, simple linear regressions were developed for the maximum and minimum temperatures between each of our sites and each of the corresponding NOAA sites. The regressions were based on the 1977-1978 and 1978-1979 data. Chi-squared tests were used to check whether the 2-year regressions were sufficient or if yearly or monthly regressions were needed. The chi-squared tests showed no significant differences in the methods; therefore, for simplicity, the 2-year regressions were used. Because there were three weather stations for each field site, the three predicted temperatures were averaged for the final estimate. A list of field sites, weather stations and calculated curve slopes, intercepts and correlation coefficients are listed in Table 2. Tribune had only one NOAA station near the field site with an acceptable correlation.

Soil Temperature Estimation

The soil temperature estimates were based on the air temperatures for the field site. The summary value for soil temperature was an average of the 24-hourly observations. Therefore, an average air temperature was used in the procedure to estimate average soil temperatures. The average air temperature was calculated from the maximum and minimum for the day rather than the 24-hourly values, because only the maximum and minimum were calculated for missing air temperatures.

The data used to determine the empirical functions were the observed soil temperatures and the corresponding air temperatures. Estimated air temperatures were included in the analysis. The initial correlations between air and soil temperature were between 90 and 94 percent. This correlation was improved by lagging the air temperature and separating winter data from the rest of the year.

To find the best lagging scheme for average air temperature, a one to eight day lag and various weighting schemes were tried. The final selection of the

Table 2. Calculated Coefficients for Estimating Air Temperatures

Site/ Weather Station	Maximum Temperature			Minimum Temperature		
	Slope	Intercept	r	Slope	Intercept	r
Albin, WY						
Kimball, NE	0.934	-0.615	0.975	0.898	-0.584	0.916
Harrisburg, NE	0.907	-0.337	0.966	0.833	-0.226	0.919
Albin, WY	0.956	-0.944	0.968	0.946	-0.771	0.959
Garden City, KS						
Garden City, KS	0.962	0.529	0.989	0.918	0.366	0.957
Lakin, KS	0.968	-0.307	0.984	0.947	0.001	0.957
Imperial, KS	0.899	0.482	0.929	0.963	0.564	0.963
Mankato, KS						
Mankato, KS	0.968	0.195	0.972	0.847	1.510	0.955
Smith Center, KS	0.953	-0.840	0.978	0.867	0.217	0.972
Red Cloud, NE	0.947	0.888	0.985	0.810	2.412	0.945
Medford, OK						
Blackwell, OK	1.003	-0.978	0.988	0.984	-0.777	0.971
Jefferson, OK	0.992	-1.899	0.983	0.956	-0.636	0.965
Paxton, NE						
Madrid, NE	0.996	-2.195	0.979	0.978	-1.377	0.977
Wallace, NE	0.996	-0.751	0.979	0.951	-0.135	0.975
Kingsley Dam, NE	1.033	-1.253	0.983	0.987	-1.538	0.973
Tribune, KS						
Tribune, KS	1.018	-1.266	0.970	0.989	0.070	0.971

best scheme was a compromise between the improvement in the correlation coefficient and simplicity. Most of the improvement occurred in the first three days of lag. For the 1-cm depth, a 2-day lag weighted 2:1 was used. For the 3-cm depth, a 3-day lag weighted 6:4:1 was used. (In each case the highest weight was the current day.) Lagging improved the correlation coefficient by approximately 2 percent.

A seasonal effect was obvious from the plots of the soil temperature data. Snow cover severely damped the temperature variation, therefore, separate regression equations were needed. Unfortunately, detailed information on snow cover was not collected. Because "snow" days were not known, all 3 years of data were used to estimate the range of dates when snow was likely at each site. The information considered was:

the observed soil temperature plots, the air temperature and precipitation values, and the remarks on the data sheets submitted by the observers. This system was not ideal because it ignored midwinter warm spells and late spring snow storms, but it was considered the best that could be done with the information. Splitting the seasons improved the correlation for the warm weather data by another 1 to 2 percent, but decreased the correlation for the cold weather to approximately 85 percent. The lower correlation reflected both the inclusion of some days that were not snowy and reduced the relationship between air and soil temperature due to the insulating effect of the snow. After estimating soil temperatures at a few sites using both sets of equations, the season-dependent equations were used despite lower correlation in winter. The estimated values for winter were in better agreement with actual data when the equation for winter was used. The final regression equations were based on all three years of data. The missing data were estimated and coded at the daily level. The regression coefficients and the dates of winter for each site are given in Table 3.

Solar Radiation Estimation

Solar radiation was estimated both at daily and hourly levels. If all or most of the hourly values were missing, then a daily total was estimated. If most of the hourly values were present, then the missing hours were estimated and the daily total was calculated from the sum of the observed and estimated hourly values. The data were coded to reflect whether daily or hourly estimation was done and which hourly values were estimated. The algorithms used in the estimation were derived using data on daily total radiation from NOAA "Class A" weather stations (NOAA, 1976-1980) and the collected hourly values.

Daily solar radiation was estimated using a two step procedure. The first step was to estimate daily clear sky radiation. We developed an algorithm to predict this from the data. This equation was:

$$QO = A + B \cos [(D*2 /365) - C]K$$

where:

- QO = Daily clear sky radiation (Langleys)
- A,B,K = Site dependent parameters determined from the data
- C = 170*2 /365 = 2.92 (170 is the day of year with peak clear sky radiation.)
- D = Day of year to calculate

Since the function was symmetric about day 170, the solar radiation at the end of the year was adjusted to make the function continuous.

After estimating the clear sky solar radiation for the day, the next step was to estimate the actual solar radiation. Rosenberg (1974) gave an equation that related percent sunshine for the day to actual solar radiation. We selected the closest NOAA weather stations to our sites that gathered percent sunshine data, to calibrate Rosenberg's equation for each of the field sites. Rosenberg's equation is:

$$Q/QO = A1 + B1*\%SS$$

- Q = Actual Solar Radiation
- QO = Clear Sky Solar Radiation
- %SS = Percent Sunshine
- A1,B1 = Site specific regression coefficients

This equation was calibrated for each of the sites for each year using the observed solar radiation data for Q, the clear sky prediction for QO, and NOAA's percent sunshine values (Table

Table 3. Calculated Coefficients for Estimating Soil Temperatures

(Dates of Winter in Day of Year)

Site/	Summer			Winter		
Dates of Winter	Slope	Intercept	r	Slope	Intercept	r
Akron, CO						
362-62						
1-cm	1.063	1.478	0.956	0.484	-0.029	0.810
3-cm	1.057	1.480	0.963	0.499	-0.041	0.792
Albin, WY						
332-100						
1-cm	0.940	1.574	0.962	0.579	0.626	0.883
3-cm	0.921	1.631	0.958	0.587	0.629	0.891
Garden City, KS						
329-69						
1-cm	0.941	1.444	0.973	0.433	0.386	0.877
3-cm	0.958	1.521	0.972	0.397	0.199	0.872
Mankato, KS						
335-91						
1-cm	0.954	1.305	0.970	0.783	0.107	0.972
3-cm	0.988	1.007	0.931	0.860	0.343	0.954
Medford, OK						
365-60						
1-cm	0.941	1.422	0.971	0.351	0.493	0.814
3-cm	0.957	1.303	0.971	0.319	0.334	0.802
Paxton, NE						
314-85						
1-cm	0.991	1.527	0.960	0.414	-0.040	0.788
3-cm	1.001	1.508	0.956	0.351	0.238	0.733
Tribune, KS						
323-96						
1-cm	0.969	1.452	0.956	0.602	1.105	0.890
3-cm	0.961	1.596	0.957	0.589	1.245	0.882

4). Daily total solar radiation was coded for the field sites.

The algorithms used to estimate hourly values of radiation were developed from the field data sets. This was also a two step procedure. The first step was to estimate the highest clear sky hourly value for each day, which occurs at solar noon. The equation used is:

$$R = R1 \exp \left\{- [(D-D1)/(D2)]^2\right\}$$

R = Clear sky radiation at solar noon (Langleys)
R1 = Maximum solar noon value for the year (Langleys)
D = Day of year
D1 = Day of year with maximum solar noon value
D2 = Curve width (days)

The values for R1, D1, and D2 were curve fit from the data. It was logical to expect that the maximum value for solar noon would occur on the summer solstice (day 172). However, the maximum occurs earlier in the spring because of increasing turbidity in the summer. Therefore, the value of D1 was set at 165 for all sites. Curve width D2 was not site dependent, and the fitted value was 200 days for all sites. The final value to be fitted, R1 - the maximum solar noon value, was site dependent and was fitted separately for each site. R1 was expected to be a function of latitude, but was not, perhaps because the latitude range was limited compared to the turbidity differences for these sites. The solar noon values are given in Table 4. Adjustment for day 353 to 365 was the same as for daily clear sky radiation.

After obtaining the clear sky solar noon values for each day, the clear sky values were calculated for each hour. The equation derived for making this calculation was:

$$R2 = R \cos [(H-HO)1/H1] + H2$$

R2 = Hourly clear sky solar radiation (Langleys)
R = Clear sky solar radiation at solar noon from the previous equation (Langleys)
H = Hour to calculate
HO = Time of solar noon - usually 12 p.m. local standard time.
H1 = Daylength (Hours). Day length was calculated from an algorithm that used latitude and day of the year.
H2 = Horizontal shift factor (our data were not always taken exactly on the hour so this allows the curve to be shifted to match our data; -0.1 shifts curve 1/2 hour earlier, and +0.1 shifts curve 1/2 hour later).

All negative values of R2 were truncated to zero for the night time period.

To estimate the missing hours, an analogous value to percent sunshine was calculated using the good hourly data. This value was the average ratio of actual solar radiation to clear sky solar radiation for each observed hour. The missing hours were then estimated by multiplying the radiation ratio from observed values by the clear sky radiation for that hour. The daily total was calculated by summing the hourly observed and estimated values. The daily summary data were coded to reflect the use of hourly data. The maximum readings for solar noon at each site are given in Table 4.

Precipitation Estimation

Precipitation was the most difficult and most subjective of the four parameters to estimate. The method used was similar to that suggested by Landsberg (1966) and Linsley et al. (1958). For each, site precipitation data from

Table 4. Solar Radiation Coefficients

(All Solar Radiation Values in Langleys)

Site/ Weather Station	Clear Sky Coef	Max Solar Noon	% SS Coef	1977-78	1978-79	1979-80
Albin, WY	A 475.2	83	Al	.419	.272	.448
Cheyenne, WY	B 258.7		Bl	.417	.603	.360
	C 2.92		r	.653	.834	.610
	K 0.95		N	125	270	235
Garden City, KS	A 492.2	85	Al	.365	.265	.349
Dodge City, KS	B 242.3		Bl	.487	.563	.542
	C 2.92		r	.848	.927	.811
	K 0.93		N	229	141	251
Mankato, KS	A 482.6	85	Al	.185	.222	
Concordia, KS	B 251.6		Bl	.639	.594	
	C 2.92		r	.846	.892	
	K 0.94		N	121	184	
Medford, OK	A 498.9	87	Al	.289	.272	
Wichita, KS	B 236.0		Bl	.617	.534	
	C 2.92		r	.828	.892	
	K 0.92		N	123	130	
Paxton, NE	A 476.2	84	Al	.256	.325	.320
North Platte, NE	B 257.8		Bl	.635	.553	.464
	C 2.92		r	.877	.849	.797
	K 0.95		N	119	196	184
Tribune, KS	A 489.8	87	Al	.499	.308	.294
Dodge City, KS	B 244.9		Bl	.347	.376	.594
	C 2.92		r	.695	.524	.794
	K 0.93		N	87	236	83

three NOAA weather stations near the site were used to develop linear regressions between our site and each of the weather stations except Tribune which used one NOAA station. As with the air temperatures, there was a time discrepancy between the wheat yield site precipitation and the NOAA precipitation values. In this case there was no way to make an exact correspondence. The data collected at 8 a.m. was shifted to the previous day, but the data collected at 6 p.m. was left within the designated day. There was very poor correlation when each day's precipitacion was used. A precipitation event was then defined on a storm basis rather than a daily event, and the storm total was used in the correlation. A storm was defined as starting when any of the four sites (the wheat site plus the NOAA sites) reported precipitation, and ending when none of the sites reported more than a trace (.01 in., or 2.5 mm). A storm total was calculated for each site and these computed values were used in the regressions. Using this definition, the correlations improved dramatically. Weather stations that still had poor correlation were excluded from the analysis.

To estimate precipitation, each file was searched for missing precipitation totals. When missing precipitation was encountered, then the NOAA sites were checked for precipitation. If all of them reported zero, then the total for each missing day was inserted as zero. If the NOAA sites had precipitation, then a storm total was calculated for each station. The storm total for each station was used in the appropriate regression equation to estimate the storm precipitation for our site. These were averaged to obtain the final storm estimate. Any precipitation totals that were recorded during the storm were subtracted from the estimate and the remaining precipitation was divided among the days of the missing data. The precipitation was either divided equally among the missing days or divided at the estimator's discretion. The site locations, NOAA weather stations, the calculated regression coefficients, and the correlation coefficients are given in Table 5.

DESCRIPTION OF METEOROLOGICAL DATA SETS

The data sets are available on magnetic tape in 19 files. The data are written on a 9 track unlabeled ASCII line image tape 1600 BPI. Record lengths are all 3200 characters. Each file consists of two header records identifying the file contents followed by meteorological data records. Each meteorological data record consists of a single day, and the number of records/site is site dependent (see Table 6). The data records include estimated data for the time period from planting to installation of weather station.

All data in each meteorological record is of the form $\pm$###.#. A code of 999 in any hourly data value indicates that the data is missing, a missing summary value is determined from the first character in the missing data code. Refer to Table 7 for a sample climatic data record.

Each file has the following structure:

Header record 1 - File name
Header record 2 - Site name and year
Meteorological data record for first day

.
.
.

Meteorological data record for last day

Table 5. Calculated Coefficients for Estimating Precipitation

(From Precipitation Measured In Inches)

SITE/ WEATHER STATION	SLOPE	INTERCEPT	r
Albin, WY			
Kimball, NE	0.648	-0.021	
0.844			
Harrisburg, NE	0.605	0.018	0.708
Albin, WY	0.370	0.022	0.704
Garden City, KS			
Garden City, KS	0.725	0.006	0.901
Lakin, KS	0.796	-0.032	0.875
Imperial, KS	1.136	-0.076	0.938
Mankato, KS			
Mankato, KS	0.698	-0.015	0.905
Esbon, KS	0.750	0.013	0.844
Lebanon, KS	0.556	0.014	0.859
Medford, OK			
Blackwell, OK	0.842	0.045	0.858
Jefferson, OK	0.662	0.118	0.789
Renfrow, OK	0.950	-0.046	0.949
Paxton, NE			
Madrid, NE	0.856	-0.010	0.893
Wallace, NE	1.039	0.006	0.883
Paxton, NE	0.922	0.012	0.875
Tribune, KS			
Tribune, KS	0.937	-0.045	0.975

Table 6. Summary of collected and estimated data.

Year/ Site	Days-of-year Start - End	Number of Records
1977-1978		
Akron, Colorado	247 - 185	304
Tribune, Kansas	252 - 183	297
Garden City, Kansas	262 - 176	280
Medford, Oklahoma	271 - 164	259
Albin, Wyoming	239 - 194	321
Paxton, Nebraska	257 - 187	296
Mankato, Kansas	267 - 186	285
1978-1979		
Akron, Colorado	255 - 190	301
Tribune, Kansas	251 - 177	292
Garden City, Kansas	291 - 73	148
Medford, Oklahoma	270 - 169	265
Albin, Wyoming	241 - 200	325
Paxton, Nebraska	259 - 192	299
Mankato, Kansas	283 - 181	264
1979-1980		
Akron, Colorado	252 - 186	300
Tribune, Kansas	259 - 162	269
Garden City, Kansas	260 - 181	287
Albin, Wyoming	268 - 191	289
Paxton, Nebraska	266 - 180	280

Each meteorological data record consists of the following data:

- Day-of-year
- Minute of hour
- Daily Summary values (11 values)
- Missing Data Codes (9 values)
- Hourly Values (24 x 9 values)
- Estimated Data Codes for Hourly Values (24 x 9 values)

Daily Summary Values consist of the following:

- Precipitation (hundredths of inches)
- Daily Wind Run (miles)
- Maximum Daily Air Temperature (°C)
- Minimum Daily Air Temperature (°C)
- Average Daily Vapor Pressure
- Average Soil Temperature at 1 cm - (°C)
- Average Soil Temperature at 3 cm - (°C)
- Total Solar Radiation - (Langleys)
- Total Reflected Radiation - (Langleys)
- Maximum Crop Canopy Temperature (°C)
- Minimum Crop Canopy Temperature - (°C)

Table 7. Hourly and daily summary climatic data for Akron, Colorado, December 31, 1977.

DAY - 364 MIN - 27

HR	PREC	WIND	ATP	VP	STP1	STP2	SRAD	RRAD	CCT	MISSING
0	0	15	-8.8	999	-3.3	-6.3	0	999	999	PCD=000
1	0	25	-7.8	999	-3.6	-6.3	0	999	999	WIND=103
2	0	33	-7.8	999	-3.8	-6.6	0	999	999	ATP=103
3	0	32	-8.3	999	-4.1	-7.0	1	999	999	VP=024
4	0	40	-8.2	999	-4.3	-7.2	1	999	999	STP1=1-4
5	0	52	-8.2	999	-4.5	-7.2	1	999	999	STP2=104
6	0	43	-9.3	999	-4.6	-7.3	1	999	999	SRAD=103
7	0	55	-9.9	999	-4.7	-7.5	1	999	999	RRAD=024
8	0	55	-8.0	999	-3.6*	-5.0*	2	999	999	CCT=024
9	0	55*	-4.0*	999	-2.6*	-2.6*	7	999	999	
10	0	55*	.1*	999	-1.5*	-.1*	13*	999	999	
11	0	54*	4.2*	999	-.4*	2.3*	19*	999	999	
12	0	54	8.2	999	.6	4.8	25	999	999	
13	0	62	11.2	999	2.1	7.2	27	999	999	
14	0	79	11.3	999	3.0	8.1	20*	999	999	
15	0	68	10.3	999	3.9	7.2	17	999	999	
16	0	35	8.8	999	3.6	5.5	11	999	999	
17	0	25	4.9	999	2.5	2.3	4	999	999	
18	0	18	1.6	999	1.1	.2	0	999	999	
19	0	34	-.4	999	.2	-1.1	0	999	999	
20	0	52	-1.3	999	-.5	-1.8	0	999	999	
21	0	55	-2.0	999	-1.0	-2.5	0	999	999	
22	0	51	-3.3	999	-1.2	-3.2	0	999	999	
23	0	41	-4.0	999	-1.6	-3.7	0	999	999	
DAILY	TOTAL	TOTAL	MAX-MIN	AVG	AVG	AVG	TOTAL	TOTAL	MAX-MIN	
SUMMARY	0.00	108.8	11.9-10.0	999	-1.2	-1.6	105	999	999 999	

* Indicates estimated data.

Missing Data Codes

A missing data code is associated with each weather parameter for each day and consists of a three digit code indicating the status of each type of data of the form 'YXX'.

The 'XX' corresponds to the number of hourly values that were originally missing. The code '00' indicates no values were missing while '24' indicates that all 24 hourly values were missing.

The 'Y' indicates if data has been estimated: '0' if no values have been estimated, '1' if the hourly values have been estimated and '2' if only the daily summary value has been estimated.

000 indicates no values were missing and the daily values were determined from the hourly data.

0XX indicates that XX hourly values still missing and no daily value is present.

1XX indicates that XX hourly values were originally missing but were estimated and then daily values were determined from the hourly data.

2XX indicates that XX hourly values are still missing and the daily estimate is independent of the hourly values.

Hourly Values (24 sets of 9) are as follows:

Precipitation - (hundredths of inches)
Wind Run (miles)
Air Temperature (°C)
Vapor Pressure
Soil Temperature - 1 cm (°C)
Soil Temperature - 3 cm (°C)
Solar Radiation (Langleys)
Reflected Radiation (Langleys)
Crop Canopy Temperature (°C)

Estimated Data Codes

The hourly estimated data codes (9 X 24 values) are used to indicate if a particular hourly value was estimated. A code of "0" indicates that the hourly value was not estimated while a code of "1" indicates that the hourly value was estimated. The estimated data codes occur in the following order.

Precipitation	(PCP)
Wind	(WIND)
Air Temperature	(ATP)
Vapor Pressure	(VP)
Soil Temperature - 1 cm	(STP1)
Soil Temperature - 3 cm	(STP2)
Solar Radiation	(SRAD)
Reflected Radiation	(RRAD)
Crop Canopy Temperature	(CCT)

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245

CHAPTER 5. DEVELOPMENT OF AGROMETEOROLOGICAL MODEL INPUTS FROM REMOTELY SENSED INFORMATION

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INTRODUCTION

The agrometeorological models referred to in the title are models such as those described in Chapters 10 and 11. We accept those as "givens". Remotely sensed information is defined as noncontact observations in one or more wavelength intervals in the range 0.35 µm (lower limit of visible light) through 14 µm (thermally emitted electromagnetic radiation). The extent of use of remotely sensed information in agrometeorological models depends upon the relative availability of remotely sensed as compared with traditional data input sources, and on the expertise and biases of the individual or group applying the model(s). Microwave (1 to 30 cm wavelength) observations would be useful by are not generally available.

Remotely sensed information can be used in two main modes in conjunction with an agrometeorological model: (a) to provide estimates of one or more specific inputs that "drive" the model, e.g. leaf area index (LAI) or intercepted photosynthetically active (0.4 to 0.7 µm) radiation (IPAR); or, (b) to provide independent feedback to override and reset or replace the model simulated canopy development or yield estimates (Wiegand 1983). In mode "a" the spectral data provide an alternative way of acquiring the necessary inputs for the model. In mode "b," for example, the LAI simulated by the model is compared with LAI estimated by handheld, aircraft- or spacecraft-mounted sensors viewing the same field(s) the model is being executed for and a decision can be made to override and reset the model. Since this feedback capability is lacking in most agrometeorological models at present, there is interest in a third mode of using spectral data--to provide its own assessment of crop yield.

The advantage of the spectral approach is that it involves a direct look at the crop canopies. The canopies achieved are responsive to within and among field variations in stresses (soil water, nutrient level, nematodes, diseases, salty soil, herbicide residues, atmospheric pollutants), past and present management and cultural practices (residual fertility, tillage, crop residue management, growth regulator applications) and soil types that are difficult to include in traditional models (Wiegand 1983). The canopy manifestations of these soil and aerial environment variations lessen the need for detailed knowledge of management practices in individual fields and increase the feasibility of applying the models to large areas (Wiegand and Richardson 198_).

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By deploying the sensors on aircraft or spacecraft, all the fields in a large area, e.g., the Great Plains, are observable. The traditional way of achieving equivalent checks is by field visits. Such visits are economically unfeasible except for a small sample of the fields. The spectral observations also help quantify stresses (Chapter 6; Wiegand et al. 1983) and verify whether the crop stands survived episodic events such as drought, flooding, and low winter temperatures (Chapter 12). Thus the use of spectral observations in conjunction with an agrometeorological model increases confidence that the model is tracking the actual behavior of plants in individual fields.

PROGRESS UNDER ARS WHEAT PROJECT

At the first meetings of the scientists and administrators to define and plan the project, there was limited awareness and even skepticism about the possibilities of remote spectral observations in crop models, except by those who had been exposed to the Large Area Crop Inventory Experiment (LACIE) (McDonald and Hall 1980). However, flow charts like that in Figure 1 illustrated and interrelated spectral data and model inputs (Wiegand et al. 1977, Wiegand 1977).

Once remote observations were accepted as a legitimate part of the effort, the

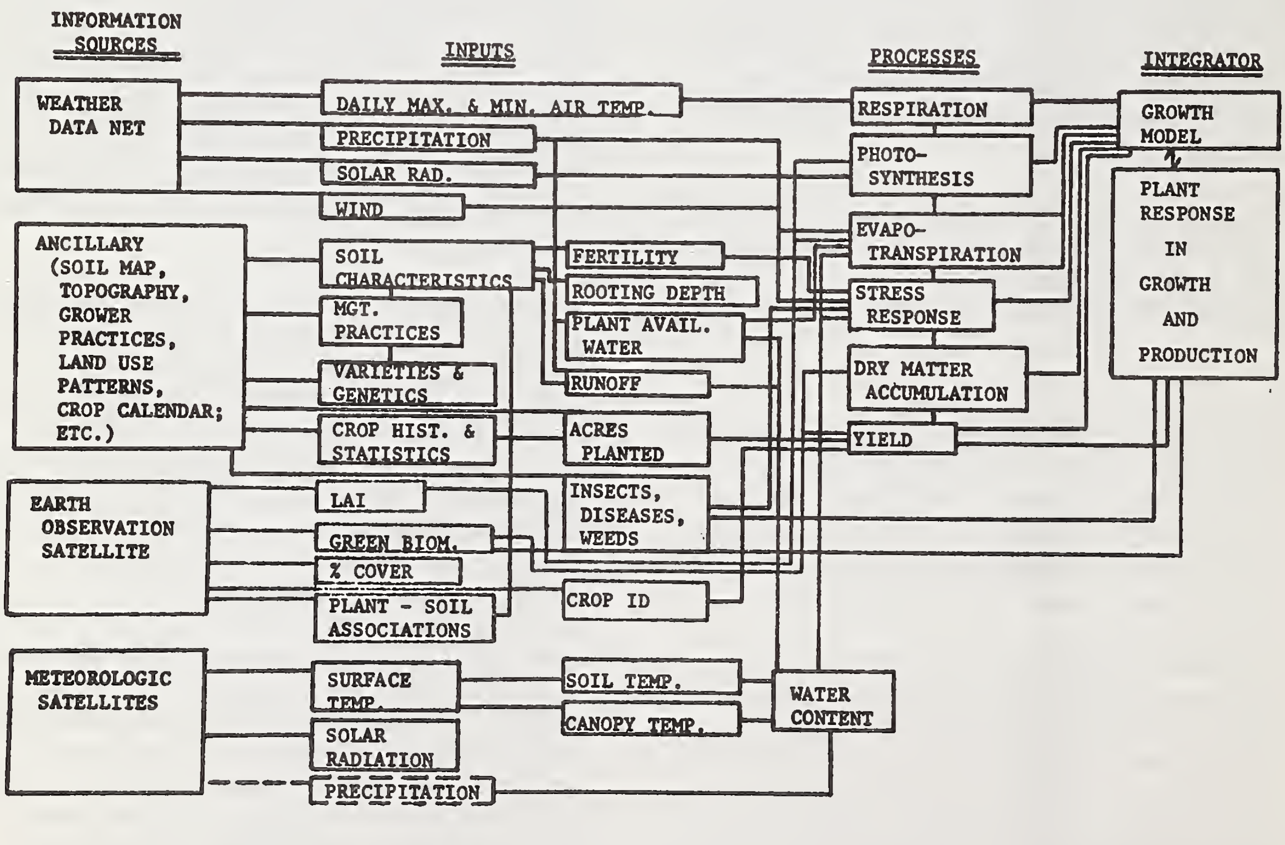

Figure 1. Information sources, inputs, and plant processes for agrometeorological plant growth and yield models. (After Wiegand 1983).

Wheat Yield Project gave a sense of mission and hence direction to the spectral measurements that would otherwise have been lacking. The project also exposed an additional increment of scientists to spectral observations. The early decision of the project's leadership to acquire and disperse handheld radiometers (Tucker et al. 1980) and data loggers (Polycorders®)[2] to the project's participants, and the workshop held on their use (Jackson et al. 1980) were important contributors to many excellent experiments that have been conducted under the impetus of and with at least partial funding from the ARS Wheat Yield Project. The experiments have dealt with a large set of issues that contribute directly or indirectly to use of spectral data in models by documenting relationships that exist, providing new understanding of scene and atmospheric behavior, convincing the scientific community of the validity and information content of the spectral measurements, acquiring data sets for testing hypotheses and relationships, developing interpretation skill and meaning, and providing insights to support integration of spectral observations into crop models.

Examples of subject matter areas researched and documenting publications include:

1. Spectral-agronomic relations (Aase and Siddoway 1980, Hatfield et al. 198_a, Tucker et al. 1980a).

2. Spectral-temporal and spectral-phenological relations (Leamer et al. 1978, Tucker et al. 1979, Pinter et al. 1981, Richardson et al. 1982, Pinter et al. 1983).

3. Development and testing of spectral transforms, vegetation and soil indices, their relation with canopy characteristics (LAI, green biomass, percent cover, chlorophyll content, phytomass), and interpretation techniques (Aase 1978, Richardson and Wiegand 1977, Jackson et al. 1980, Lautenschlager and Perry 1981, Aase and Siddoway 1981a, Wiegand and Richardson 1982, Huete et al. 1983, Perry and Lautenschlager 1983).

4. Examination of wavelengths in addition to the Landsat wavelength intervals (0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, and 0.8 to 1.1 μm) for utility and information content (Leamer et al. 1978, Jackson 198_).

5. Developing procedures to achieve agreement between space (top of atmosphere) and ground-observed reflectance factors (Richardson 1982, Richardson 1983, Jackson et al. 1983, 1983a).

6. Scene spectral modeling including effects of atmosphere, sun and view angles, and planting configurations on observations (Jackson et al. 1979, Le Master et al. 1980).

7. Development of spectral measures of stress (Tucker et al. 1980, Jackson et al. 1982, Wiegand et al. 1983).

8. Spectral estimates of yield (Idso et al. 1979, Idso et al. 1980, Tucker et al. 1980, Aase and Siddoway 1981, Wiegand and Richardson 198_).

9. Spectral inputs or surrogates for agrometeorological models (Wiegand et al. 1977, Wiegand et al. 1979, Wiegand 1983, Wiegand and Richardson 198).

[2] Product names are given for information purposes and do not imply consent or endorsement by USDA.

10. Plant development scale comparisons (Bauer et al. 1983).

Selected exemplary figures, tables, and equations from these publications illustrate the progress that has been made. Many researchers have verified that a variety of vegetation indices--differences, ratios, and linear transformations of spectral observations (Richardson and Wiegand, 1977; Lautenschlager and Perry, 1981; Aase and Siddoway, 1981)--relate to crop canopy "greenness." As an example of one vegetation index, Figure 2 (after Aase and Siddoway 1981) shows that leaf biomass is related to the normalized difference (ND) defined by (MSS7 - MSS5)/(MSS7 + MSS5) where MSS5 and MSS7 denote the reflectance in visible red (0.6 to 0.7 μm) and reflective infrared (0.8 to 1.1 μm wavelengths, respectively. Lautenschlager and Perry (1981) and Perry and Lautenschlager (1983) have demonstrated that a number of the vegetation indices (VI) are mathematically equivalent. Their value is that they condense observations in two or more wavelengths to a single number that relates well the amount of photosynthetically active or chlorophyll-containing tissue. Thus the VI relate well to LAI, percent cover by green vegetation, leaf weight, green or dry biomass of nonstemmy vegetation, and chlorophyll content per unit area. All of these indices relate to the crop's light interception capacity. Consequently, they relate to the health or vigor of a crop and to development stage until the canopy is sufficiently developed that the incident insolation is fully intercepted.

On most of the Great Plains, water and other constraints usually prevent rainfed wheat from achieving a canopy dense enough to fully intercept the light. But since seeding rates and management practices are tuned to location spe-

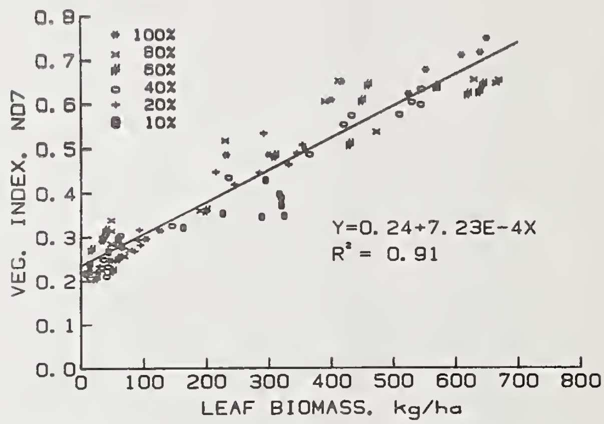

Figure 2. Normalized difference vegetation index (ND7) versus leaf biomass for six spring wheat stand densities, expressed as a percentage of normal seeding rates. (After Aase and Siddoway 1981).

cific climate and soil constraints, the harvest index of wheat is remarkably constant even on the western Great Plains (Aase and Siddoway 1981). Because high yields cannot be achieved unless the crop canopy development is sufficient to intercept most of the incident insolation during the reproductive phase, the spectral measurements frequently correlate well with yield.

In Figure 3, taken from Tucker et al. (1980a), the coefficients of determination, r^2, between grain yield and two VI are summarized for 21 observation dates during the winter wheat growing season. The two VI are the reflective infrared/red ratio and the ND as previously defined. There was a 5-week period, from stem elongation through anthesis, over which the spectral data explained approximately 64% of the grain yield variation. Aase and Siddoway (1981a) reported that the highest correlation between spectral

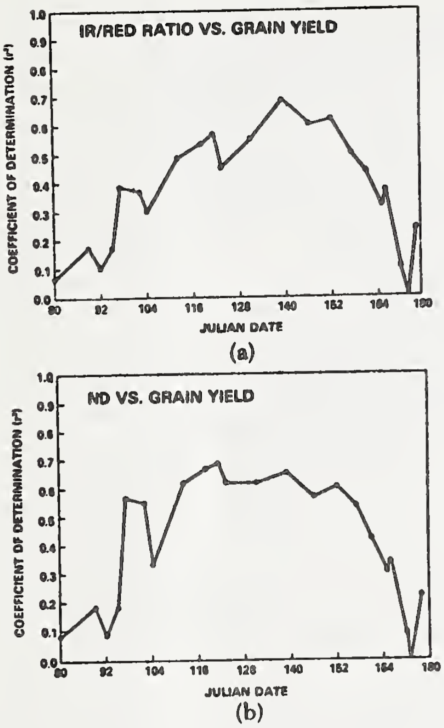

Figure 3. Coefficients of determination resulting from regressing the (a) IR/RED radiance ratio or (b) normalized difference (ND) against grain yield for each of 21 collection dates. Note that the ND was more highly correlated with final grain yield earlier in the season than was the IR/RED radiance ratio. (After Tucker et al. 1980a).

indices and yield were obtained from stem elongation through watery ripeness of the grain. The reason the relations are best through early grain filling is that the green leaf area index (GLAI)[3] reaches a maximum at about boot stage and declines throughout grain filling. Consequently, the later in grain filling the spectral observations are made, the more the photosynthetically inactive tissue dominates the observations and the relationship degrades.

Pinter et al. (1981) used a somewhat different approach (Figure 4). They summed the normalized differences daily for the period from heading to full senescence for all ND above the base value for harvest-ready (fully senescent) crops of wheat and barley. Thus, they took into account not only the greenness of the canopy but also its persistence. For Produra wheat whose canopy development had been affected by timing and amount of irrigation water applied, the summed ND accounted for 88% of the yield variation. However, because the duration of grain filling in temperate cereals, including wheat, is temperature dependent (Wiegand and Cuellar 1981), any method analogous to leaf area duration cannot hold across environments (Evans and Wardlaw 1976).

The temporal spectral measurements, such as shown in Figure 4 are valuable for following the pattern of canopy development. For example, a leveling off in vegetation index during the period of normal, rapid development of the canopy may well correspond to a gradual depletion in soil water, especially if a rapid rise in the VI is observed following a known rainfall event. The vegetation index behavior would correspond to a decrease in growth (production of leaf and canopy) during a water stress period and "boom" growth upon relief by the rain. Other stresses are similarly manifested through the canopy observations (Chapters 6 and 12). For wheat and other temperate cereals, the decline in VI following anthesis can be quantified into a senescence rate (VI day^{-1}) that can be related to agronomic and environmental conditions. Idso et al. (1980) have even proposed that yields be estimated from senescence rates.

[3] The ratio of the area of green leaves to the ground areas occupied on the whole field basis.

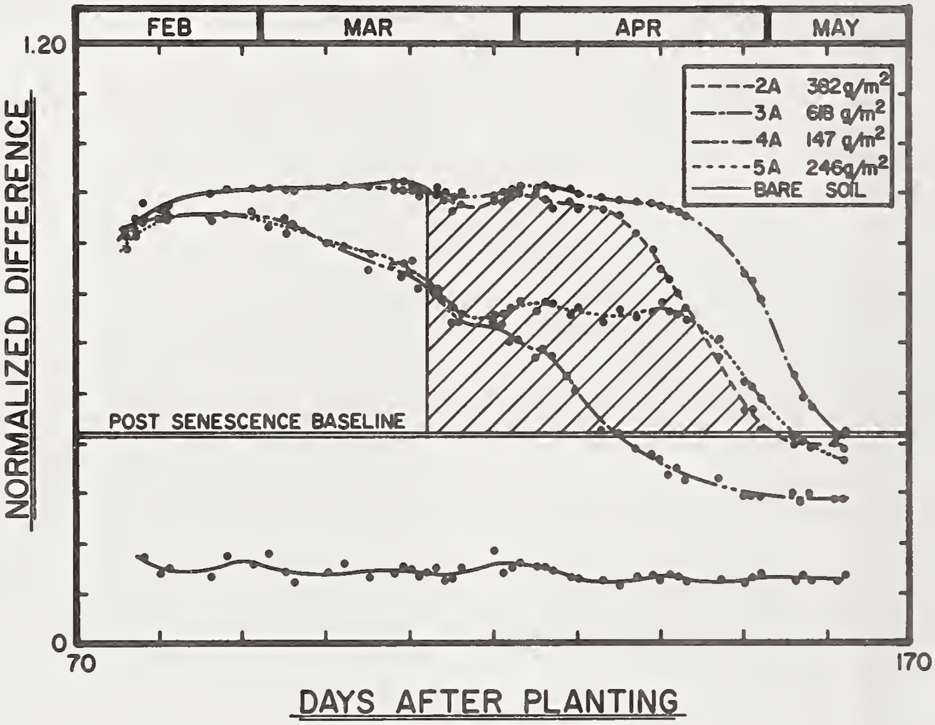

Figure 4. The normalized difference (ND) versus time after planting for four Produra wheat fields with widely varying yields and a bare soil plot in 1977. The shaded portion under the curve for plot 2A is a graphic representation of the integration technique described in the text. (After Pinter et al. 1981).

Wiegand and Richardson (198_) have proposed equations that interrelate the information conveyed by plant canopies about their development (or restraint from development by stresses), light interception capability, and yield performance. The equations are

$$\frac{\ln LAI}{VI} \times \frac{Yield}{\ln LAI} = \frac{Yield}{VI} \qquad [1]$$

$$\frac{\ln LAI}{VI} \times \frac{IPAR}{\ln LAI} = \frac{IPAR}{VI} \qquad [2]$$

where VI denotes any one of several spectral vegetation indices available, IPAR is intercepted photosynthetically active radiation, and yield is grain yield.

Essentially, the integral VI are estimates of integral intercepted solar radiation which Daughtry, et al. (1983) and Hatfield et al. (198_) have shown can be estimated spectrally. Since the IPAR vs ln LAI relations available in the literature and already in use in the agrometeorological models can be transferred directly to equation [2], it becomes possible to estimate IPAR remotely. This means in effect that IPAR generated by the models can be checked by direct observations. Where the relation between LAI and VI is known from previous studies, such as it is for wheat, the VI's can also serve to check on the model's estimates of LAI.

From historical LANDSAT or the currently available NOAA meteorological

satellite data, it is possible to establish the relation between yield and the VI on field (LANDSAT) or county or crop reporting district synoptic scales (NOAA) from the VI observations those sensors provide and the yield data reported annually by the Statistical Reporting Service. Wiegand, et al. (1983) and Wiegand (1983) report such a relation for grain sorghum (Sorghum bicolor L., Moench) in South Texas, established during grain filling of the crop. By definition the difference between the spectral estimate for the current year and the long term average is the production deviation from the average. Such information when available in advance is useful in preparing to harvest, transport, store, and market the crop.

The possibility of quantifying stress effects on yields through their effects on the canopies achieved is an exciting one. Although the literature on stresses is voluminous, ways to relate stresses meaningfully to yields have been lacking. Spectral observations to quantify stresses and relate them to yield merit further emphasis.

Table 1 summarizes additional opportunities to augment agrometeorological models with remote spectral observations. The table is organized by the subroutines (photosynthesis, growth or dry matter accumulation, evapotranspiration, phenology, stress, and yield) usually found in the growth/yield models. A number of the possibilities are hypothetical in that there is no known test in the literature, although tests are technically feasible. Others depend, for acceptance, on the outcome of tests of the relations expressed by equations [1] and [2]. Still others depend on the availability of suitable data sets. We trust that the data sets provided by the ARS Wheat Yield Project will be a suitable one for such research.

A point worth making is that there is no past experience on using and incorporating remotely sensed observations into crop/growth yield models because such observations have not been previously available. Also, the available remote observations are evolving; e.g., within a year NOAA expects to be providing surface temperature (canopy temperature when the canopies are well developed) and precipitation estimates from the Advanced Very High Resolution Radiometer (AVHRR) aboard the operational meteorological satellites. Thus the models used will evolve gradually.

An important aspect of any successful effort will be data bank and data base management. As shown in Figure 1 there are myriad sources of relevant information that could be acquired, archived, merged and processed to extract that needed to execute models. With current pressures on food, fuel, fiber, and forage vegetation resources, the ARS scientists involved are working on a project with global consequences. In general, we feel that many of the candidate spectral inputs of Table 1 are now ready for testing and adaptation for incorporation into crop growth/yield models.

SPECTRAL OBSERVATIONS OF ARS WHEAT YIELD PROJECT FIELDS

Landsat and a limited amount of handheld radiometer data were collected for both winter wheat and spring wheat fields for the crop years 1977-'78 through 1980-'81 (Chapter 7). Figure 5 presents the relations between the vegetation index, perpendicular vegetation index (PVI) (Richardson and Wiegand 1977) derived from Landsat-2 observations and two ground-truthed plant parameters, tillers/m^2 and dry matter

Table 1. Remotely sensed inputs or feedback to agrometeorological models grouped by model subroutines.

Model Subroutines	Remotely Sensed Input or Check
Growth or dry matter accumulation	VI[a]--spectral surrogate of green biomass --spectral profile[b] -- growth rate
Photosynthesis	VI--spectral surrogate of LAI for light absorption estimate Light absorption model--Chance and LeMaster, 1978 Spectral estimates of IPAR
Evapotranspiration	BR or SLI[c]--albedo, surface wetness --ground cover for partitioning evaporation and transpiration Tc-Ta[d]--as related to ratio of actual to potential evapotranspiration, E/Ep
Phenology	Spectral profile--emergence or green-up date, maximum greenness date Tc--in lieu of air temperature to pace ontogenetic events
Stress	VI--Canopy "greenness" and magnitude vs. normal; senescence rate Tc-Ta--stress severity diagnostic, or in crop water stress index, (1-E/Ep)
Yield	VI--near maximum canopy development or early in grain filling; spectral profile integrals

[a] VI = spectral vegetation indices GR, PVI, ND, etc. (see text)
[b] Spectral profile = vegetation index vs. time (see fig. 4, e.g.)
[c] BR, SLI = brightness and the soil line index, spectral indices dominated by soil background. (see Kauth and Thomas 1976; Wiegand and Richardson 1982)
[d] Tc is canopy temperature; Ta is air temperature

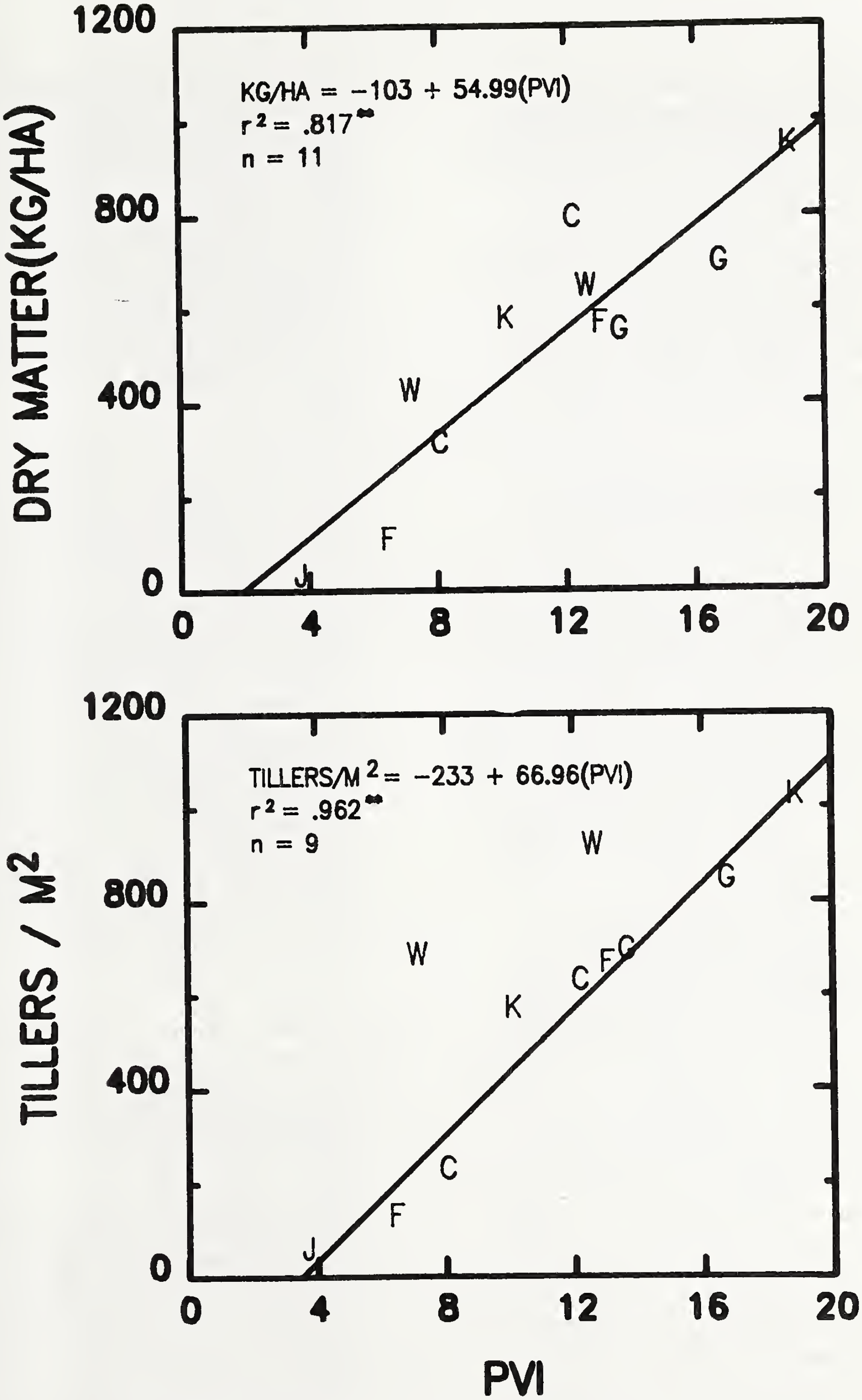

Figure 5. Relation between perpendicular vegetation index (PVI) and two plant characteristics (tillers/m^2 and dry matter, kg/ha) during the fall growth period of the ARS Wheat Yield Project fields in the 1977-'78 season. Fields are located in Keith (K) Co., NE; Grant (G) Co., OK; Washington (W) Co., CO; Finney (F) Co., KS; Greeley, (C) Co., KS; and Jewel (J) Co., KS.

(kg/ha). The data are for the fall growth period preceding winter dormancy. There are two observation dates for five of the fields and one observation date for the Jewel Co., KS, field. There are no observations of the Banner Co., NE, field because the crop strips were too narrow to resolve with the 80 m instantaneous field-of-view Landsat system. The Landsat data were adjusted for solar zenith angle and atmospheric haze.

The coefficient of determination between PVI and tillers/m^2 for the sites except Washington Co., CO, is 0.96 whereas it is 0.82 between PVI and dry matter including the Washington Co., CO field. The slopes of the regression equations indicate there are 67 tillers/m^2 per unit PVI and 55 kg/ha dry matter per unit PVI. We do not know why the Washington Co. data do not fall in line with the other sites. If tiller leaves differed greatly in size for the cultivar grown there compared with the other sites, then the biomass would also have differed.

In general, the relation between tillers/m^2 in Figure 5 and PVI should be similar to that for dry matter and PVI for two reasons: (a) the biomass at this developmental stage consists almost totally of chlorophyll- containing leaf blades and sheaths, and (b) new tillers appear in the axils of existing tillers when the fourth leaf on the tiller is about half expanded (Chapter 8). But the r^2=.83 between tillers/m^2 and dry matter (not shown) is no better than between the top of the atmosphere Landsat observations and these parameters.

The ability to estimate tiller population spectrally is useful for establishing the plant population needed as initial input to the models. (For a short time after emergence only primary tillers exist, so the tiller population is the plant population.) Also, the number of tillers estimated soon after spring greenup compared with the number prior to winter dormancy indicates the number that survived the winter. The tiller estimates may also be of value in checking on the number estimated by the agrometeorological model used; number of tillers has not been easy to mimic accurately in agrometeorological models.

The handheld and Landsat observations for the ARS Wheat Fields constitute a rich data set for comparing the agrometeorological model performance against actual plant behavior when operated in the traditional way vs. with spectral estimates of such inputs as tillers/m^2, LAI and IPAR. A high priority needs to be placed on producing algorithms for resetting and continuing the execution of agrometeorological models when remotely sensed canopy observations are used as feedback to the models. There also needs to be a well-planned effort devoted to study of the spectral data--possibly predesignating some of them for developing relationships for spectral inputs to models and some for testing them. These studies would determine such things as variability in the soil line among geographic sites and its consequences on the VI; the mathematical forms and calibrations of the terms in equations [1] and [2]; atmospheric variation and path radiance effects and ways to cope with it; and, development of a stand-alone spectral model. Useful information from all these efforts then needs to be transferred to operational users such as the SRS, FAS, and SCS in USDA.

SUMMARY

The progress made in developing and using spectral information promises to

augment and enhance the agrometeorological models by providing direct evidence of canopy condition that can be interpreted in terms of number of tillers, LAI, or IPAR for direct use in the models, or as feedback to them. Thus, use of spectral observations in conjunction with agrometeorological models increases confidence that the correct deductions are being made. In several instances the spectral data appear to be a meaningful way to quantify stresses--through their effects on the canopies the crop achieve. As a consequence of the constancy of the harvest index of wheat and environmental constraints on the canopies achieved over most of the Wheat Belt, grain yield of wheat relates well to spectral vegetation indices during the period late stem extension to early grain filling. Collectively these findings help determine whether or not agrometeorological model estimates of plant canopy characteristics, that in turn, affect the model's photosyntheses, evapotranspiration, stress response, and yield subroutines, are being correctly predicted for particular production areas.

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245

CHAPTER 6. PLANT STRESS AND STRESS-YIELD RELATIONSHIPS DETERMINED USING REMOTELY SENSED DATA

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INTRODUCTION

The formation of the ARS Wheat Yield Project in the mid-1970's coincided with the initiation of a research program at the U. S. Water Conservation Laboratory whose purpose was to develop methods that used remotely sensed data to assess plant water stress in the field. Since both severity and duration of stress are detrimental to plant growth, it was recognized that an index of stress, integrated over the growing season, should be related to harvestable yield.

Initially, our research focused on developing measures of stress using remotely sensed plant temperatures calculated from measurements of emitted radiation in the thermal-infrared region. Subsequently, radiometers that respond to radiation in the visible and near-infrared regions were obtained. Data in the three regions of the electromagnetic spectrum were collected throughout seven wheat growing seasons. Several stress indices were developed during this period, some of which were related to harvestable yield. In the following sections, these indices and stress-yield relationships are reviewed. For the most part, the discussion concerns measurements on wheat. However, data for other crops such as alfalfa and cotton are occasionally used to illustrate a particular concept.

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TEMPERATURE BASED STRESS INDICES

A review of the meteorological, soil, and plant factors that are used to signal water deficits shows that meteorological and soil factors indicate when plants may be stressed, and plant factors indicate when they are stressed. It is obvious that plant factors are the best indicators of biological stress, although the meteorology of the environment plays a significant role. Plant factors, such as xylem water potential, leaf diffusion resistance, and leaf photosynthesis are point measurements that require either destructive sampling of parts of individual plants or large investments in time and equipment to adequately characterize a field. Canopy temperature measurements made with infrared radiometers circumvent these problems because they are noncontact and can include a large number of plants in the field-of-view of the instrument.

The stress-degree-day (SDD), which is the canopy-air temperature difference measured post-noon near the time of maximum heating, was perhaps the first stress index that was based on infrared temperature measurements (Idso et al. 1977, Jackson et al. 1977). In the development of the SDD, it was assumed that effects of environmental factors (such as vapor pressure, net radiation, and wind) would be largely manifested in the canopy temperature, and that the difference between the canopy temperature (T_c) and the air temperature (T_A) would be an indicator of plant water stress. Idso et al. (1977a) related the SDD to final grain yields (see STRESS-YIELD RELATIONSHIPS). Jackson et al. (1977) evaluated the SDD as a possible irrigation scheduling tool. They measured water depletion with a

neutron moisture meter, and accumulated all positive daily values of the SDD between irrigations. It was concluded that irrigations should be given before or at the time the cumulative SDD reached a value of 10.

Ehrler (1973) measured cotton leaf temperatures using thermocouples and suggested that the leaf-air temperature difference was linearly related to the air vapor pressure deficit (VPD). Idso et al. (1981a) used thermal-IR radiometers to obtain canopy temperatures and demonstrated that a linear relation indeed existed between the canopy-air temperature difference ($T_C - T_A$) and the VPD, provided that the plants were transpiring at their potential rate. The relation was further demonstrated with data obtained for alfalfa at several locations in the western U. S. (Idso et al. 1981b), with the results shown in Figure 1. Subsequently, Idso (1982) established "non-water-stressed baselines" for a number of crops.

Monteith and Szeicz (1962) developed an equation that related ($T_C - T_A$) and VPD from energy balance considerations.

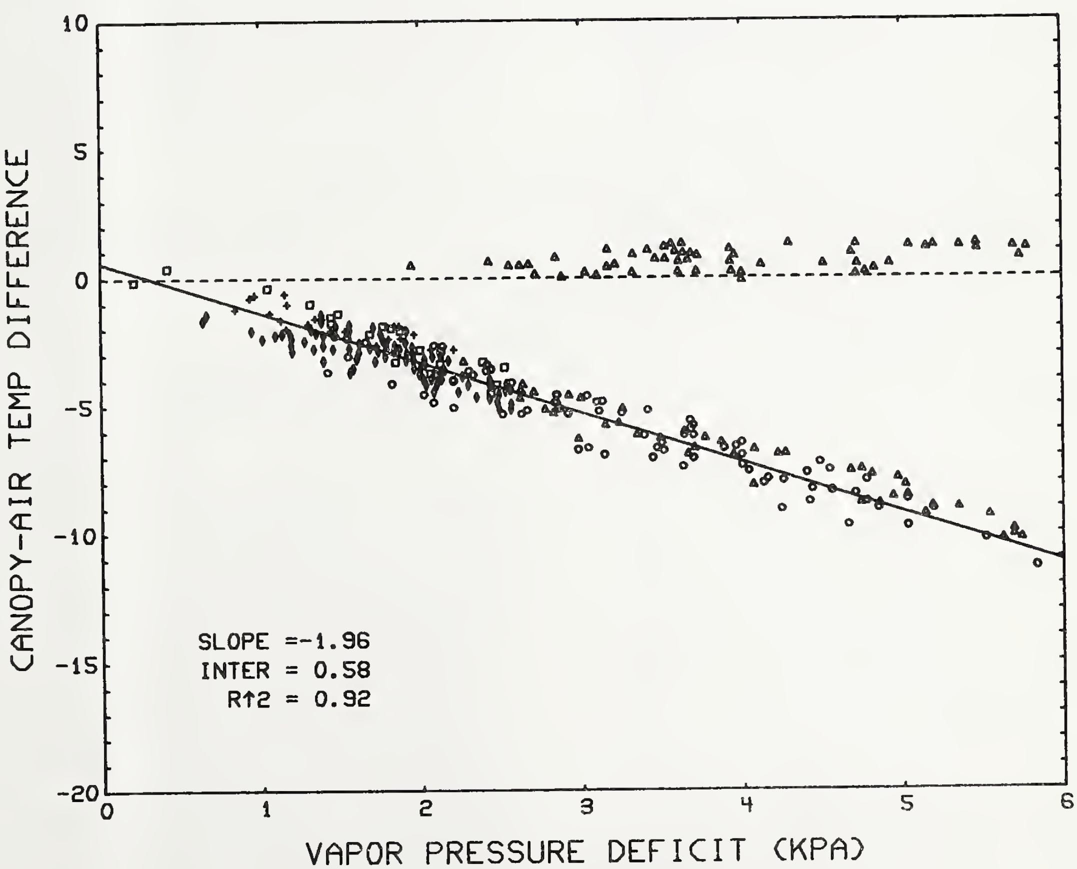

Figure 1. Canopy-air temperature differences versus vapor pressure deficity for well-watered plots of alfalfa assumed to be transpiring at the potential rate, and one severely water-stressed plot for which all temperature differences were positive.

Jackson et al. (1981) used a similar approach and presented the equation,

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma (1 + r_c/r_a)}{\Delta+\gamma (1+r_c/r_a)} - \frac{VPD}{\Delta+\gamma(1+r_c/r_a)} \quad (1)$$

where r_a and r_c are the aerodynamic and canopy resistances (sm^{-1}), R_n is the net radiation (Wm^{-2}), ρc_p the volumetric heat capacity of air (Jm^{-3} C^{-1}), γ is the psychrometric constant (PaC^{-1}), and Δ is the slope of the temperature-saturated vapor pressure relation (PaC^{-1}).

For well-watered plants the canopy resistance (r_c) is low but usually not zero (van Bavel and Ehrler, 1968). Assuming that a value of r_c = 5 sm^{-1} represents r_c at potential evapotranspiration, $T_c - T_A$ was calculated as a function of VPD. Results of these calculations are given in Figure 2. The line labeled 5 is slightly lower than the "non-water-stressed baseline" of Idso et al. (1981a). Also shown are lines for r_c = 50, 500, and ∞, which correspond to moderate, severe, and

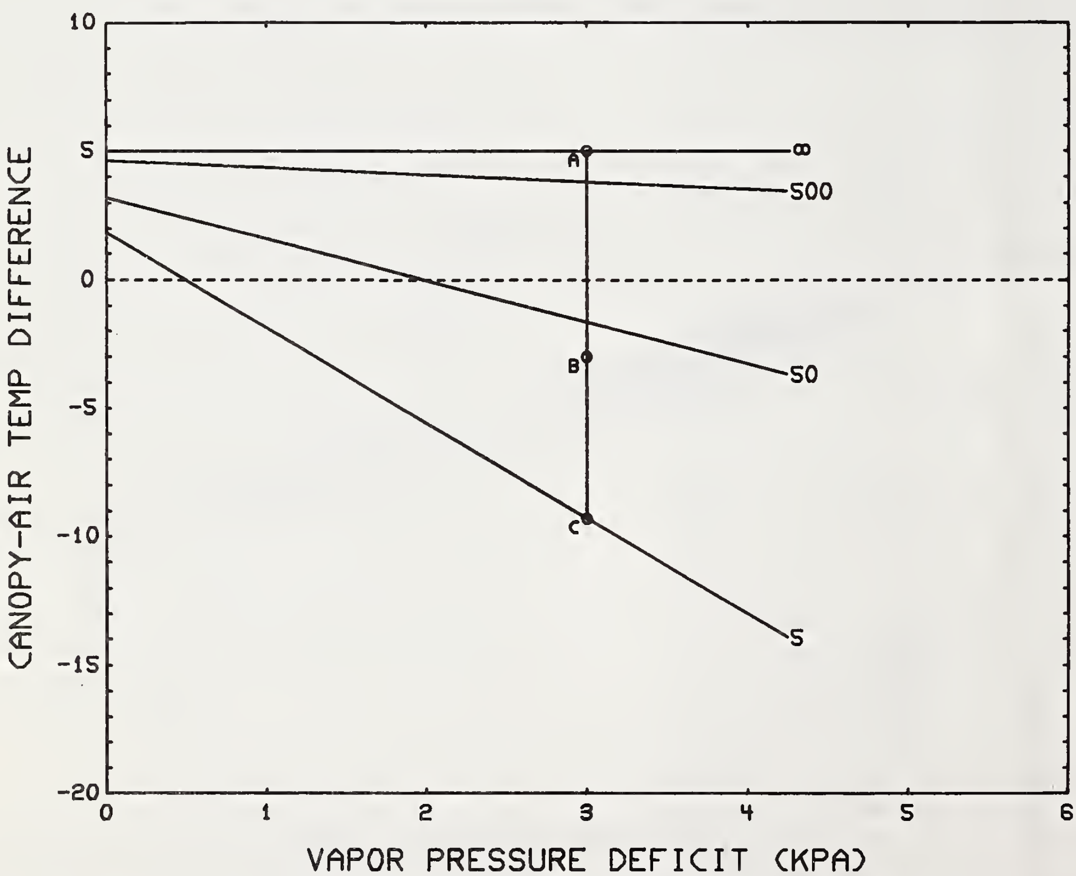

Figure 2. Theoretical relationship between the canopy-air temperature difference and the vapor pressure deficit. Numbers at the end of lines indicate the value of the canopy resistance (r_c) used for the calculations.

infinite stress, respectively. When $r_c = \infty$, Equation (1) reduces to

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \tag{2}$$

which shows that the upper limit of plant temperature is dependent on the stability corrected aerodynamic resistance and the net radiation.

Point B in Figure 2 represents a measured value of $T_c - T_A$. Points A and C represent values of $T_c - T_A$ that would occur if the plants were under maximum and minimum stress, at a particular value of VPD. Idso et al. (1981a) and Jackson et al. (1981) defined a crop water stress index (CWSI) as the ratio of the distances BC/AC. The mathematical equivalent is (Jackson et al. 1981),

$$CWSI = \frac{\gamma\ (1 + r_c/r_a) - \gamma^*}{\Delta + \gamma\ (1 + r_c/r_a)} \tag{3}$$

The term $\gamma^* = \gamma(1 + r_{cp}/r_a)$ where r_{cp} is the canopy resistance at potential evapotranspiration.

In climatic regions where plant temperatures are frequently below air temperatures, the use of air temperatures in meteorologically based yield models may cause error. During the development of a meteorologically based rice model, Neff et al. (1983) found that model parameters had to be changed for different climatic regions if air temperatures were used. When canopy temperatures were used in the model, the same parameters were applicable to the different climates. They calculated canopy temperature by using equation (1) with standard weather station air temperatures and vapor pressures as inputs.

CANOPY TEMPERATURE AND PLANT WATER POTENTIAL

The assumption that canopy temperature is a measure of plant water stress is largely based on qualitative observations such as visual wilting. Physiological processes are often affected before wilting becomes apparent, and different species may wilt at different stress levels (Hsiao, 1973). Because plant water potential has gained wide acceptance as a fundamental measure of plant water status, it is of interest to compare such measurements with canopy temperature data.

Plant water potentials can be measured by the use of a pressure chamber such as that described by Scholander et al. (1965). Whole plants, or parts of plants, can be measured depending upon plant size and species, and the chamber size. With plants such as cotton, a leaf and petiole is usually measured, whereas with small grains, the entire above-ground portion of the plant may be placed in the chamber. In either case, the sample measured is a small part of an entire canopy, and considerable variation is to be expected.

Plant water potentials were measured on whole (above ground) wheat plants on 19 clear days (at 1400h) at Phoenix, AZ by Ehrler et al. (1978a). Canopy temperatures were measured concurrently, using IR thermometers. Measurements were made on six differently irrigated plots. The results are shown in Figure 3. Even with a number of observations per plot, there was a considerable amount of scatter in the data. The line drawn through the points indicated that as stress increased (plant water potential decreased) the canopy-air temperature difference increased. The temperature difference reached a maximum of about 5°C, and then increased only slightly with fur-

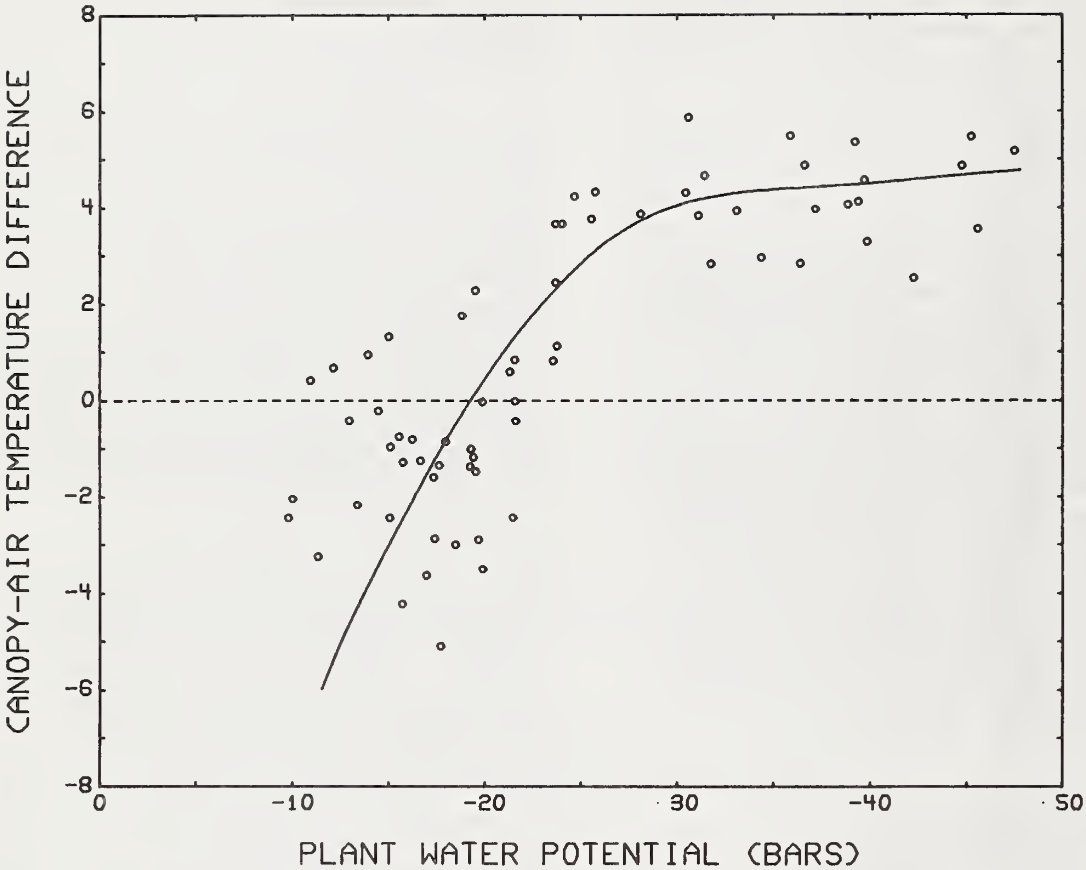

Figure 3. Temperature of the canopy minus the air temperature at 1.5 m above the crop at 1400 hours as affected by the whole-plant water potential, the data consisting of 70 points from measurements taken on 19 clear days, with each point being the mean of from 12 to 30 pressure chamber readings on separate plants, and from 4 to 12 ΔT readings. The 70 points were derived from 220 individual sets of data.

ther decrease in plant water potential. Data of Sumayao et al. (1980), if plotted on Figure 3, would fall well within the range of values shown for wheat. One can conclude from these data that canopy temperatures and plant water potential are correlated, but not linearly, and that variability due to sampling precludes a more quantitative comparison.

The diurnal change in plant water potential and canopy temperatures was documented by Ehrler et al. (1978b). The diurnal range of plant water potential was considerable, from about -0.1 to -1.6 MPa for well watered plots, and from about -2.1 to -4.3 MPa for a water deficient plot. They concluded that for canopy temperature measurement, 1400 h was the best time of day to assess water stress.

Recent studies conducted on alfalfa (Idso et al. 1981b), cotton (Idso et al., 1982a), and wheat (Idso et al. 1981c) delineated distinct components of the total plant water potential, one

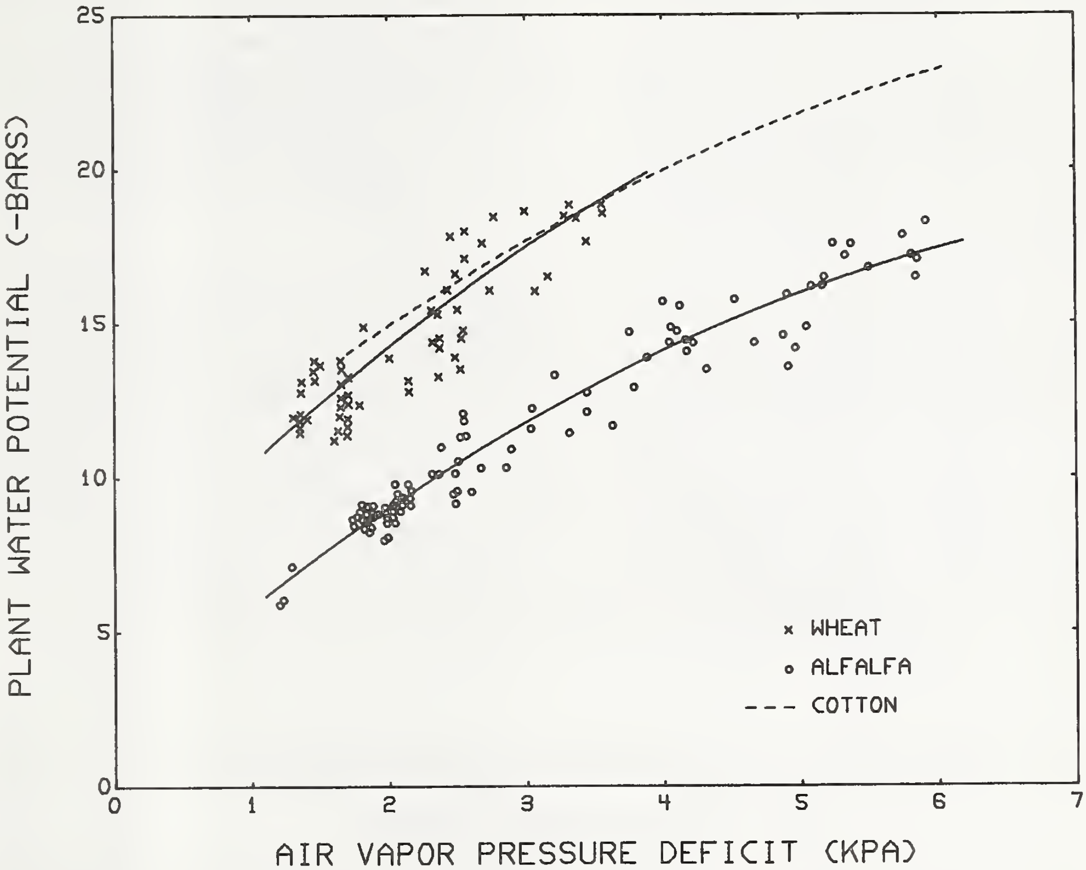

Figure 4. The atmospheric-induced component of plant water potential, i.e., total crop water potential for plants transpiring at the potential rate, vs. air vapor pressure deficit for alfalfa, cotton, and wheat. Actual data shown are for alfalfa and wheat.

being atmospheric-induced and one being soil-induced with the latter becoming operative when transpiration falls below the potential rate.

Figure 4 represents the combined results of the three separate experiments on alfalfa, cotton, and wheat, with respect to the atmospheric-induced component of plant water potential. In all cases this component was adequately specified by the air vapor pressure deficit (VPD), and results for wheat and cotton were nearly identical.

To relate the soil-induced component of plant water potential to the crop water stress index, it is necessary to delete the atmospheric-induced component from the total. This adjustment was done by measuring the air VPD and using the relationships of Figure 4 to evaluate the atmospheric component and then subtract it from the total plant water potential. When this was done in the three experiments, the results of Figure 5 were obtained. These data show essentially identical results for alfalfa and wheat, as compared to the common result for wheat and cotton in Figure 4. Reasons for these similarities and differences remain to be

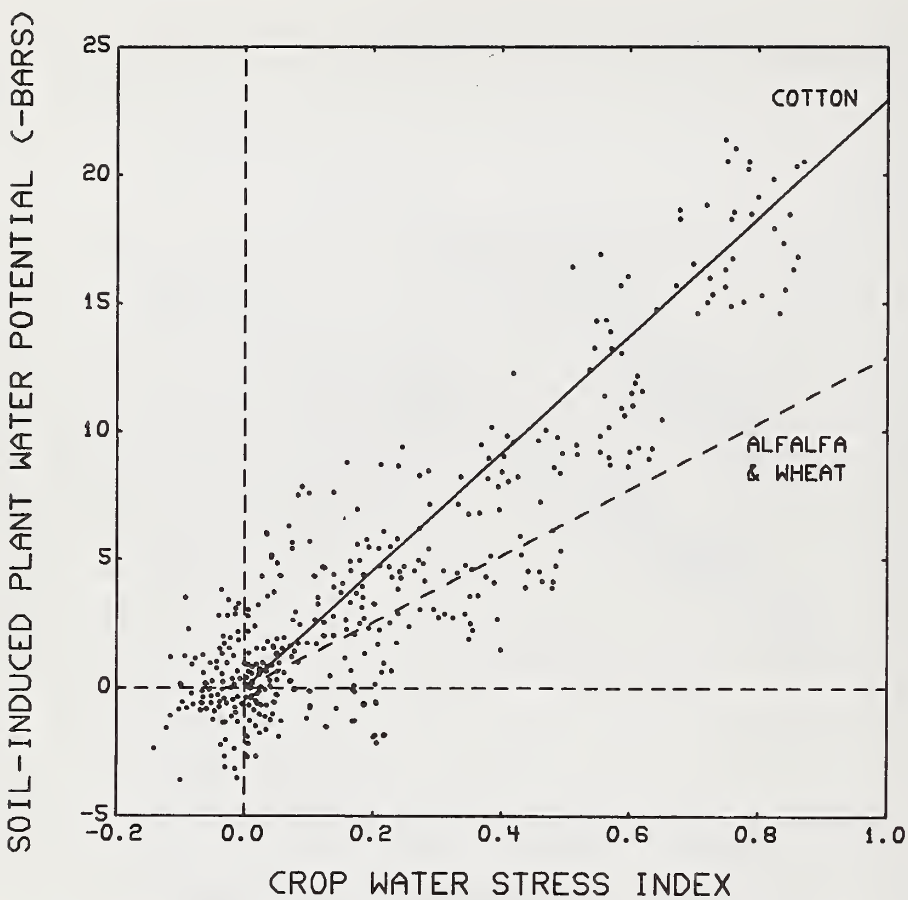

Figure 5. The soil-induced component of plant water potential vs. the crop water stress index for alfalfa, cotton and wheat. Actual data shown are for cotton. The dashed line represents alfalfa and wheat.

determined. It is obvious that there are important plant factors that moderate the responses of both components of the total plant water potential to variations in the crops soil and aerial environments.

STOMATAL DIFFUSION RESISTANCE AND NET PHOTOSYNTHESIS

The relationship between stomatal diffusion resistance and the CWSI has thus far only been determined for cotton (Idso et al., 1982b). Much work remains to be done in this area. It is evident that there is a strong dependency of the CWSI on leaf diffusion resistance, particularly for moderate to large values of the index.

The relationship of net photosynthesis to the CWSI has also been determined for cotton (Idso et al., 1982b). The net photosynthesis decreases linearly with increasing CWSI, reaching zero at an index value of about 0.9.

CANOPY TEMPERATURE AND SOIL WATER CONTENT

Thermal-IR measurements of plant canopies have been used to infer soil water

content in the root zone of crops. Idso and Ehrler (1976) related canopy-air temperature differences to the average water content in the root zone. The plant temperature-soil water relation was reasonably good at low soil water contents, but became nonunique at higher water contents.

Later, Idso et al (1982a) plotted canopy-air temperature difference data for cotton as a function of air vapor pressure deficit (VPD). A number of measurements per day allowed a time sequence to be plotted and the value of VPD at which the measurement rose above the baseline to be determined. The results showed that the point of deviation from the baseline was related to the extractable water in the top 1.7 m of soil. This procedure yielded a linear relation between extractable soil water used and the VPD above which potential evapotranspiration could not be maintained (Figure 6). This relation exemplifies the interaction of the aerial environment and soil water in determining evapotranspiration.

Jackson (1982) related the CWSI to the extractable water used by wheat. The data were obtained on plots that had received different irrigation treatments. He found that, if wheat plants were stressed and then irrigated, several days were required for the CWSI to reach a minimum, whereas the extractable water used attained a minimum

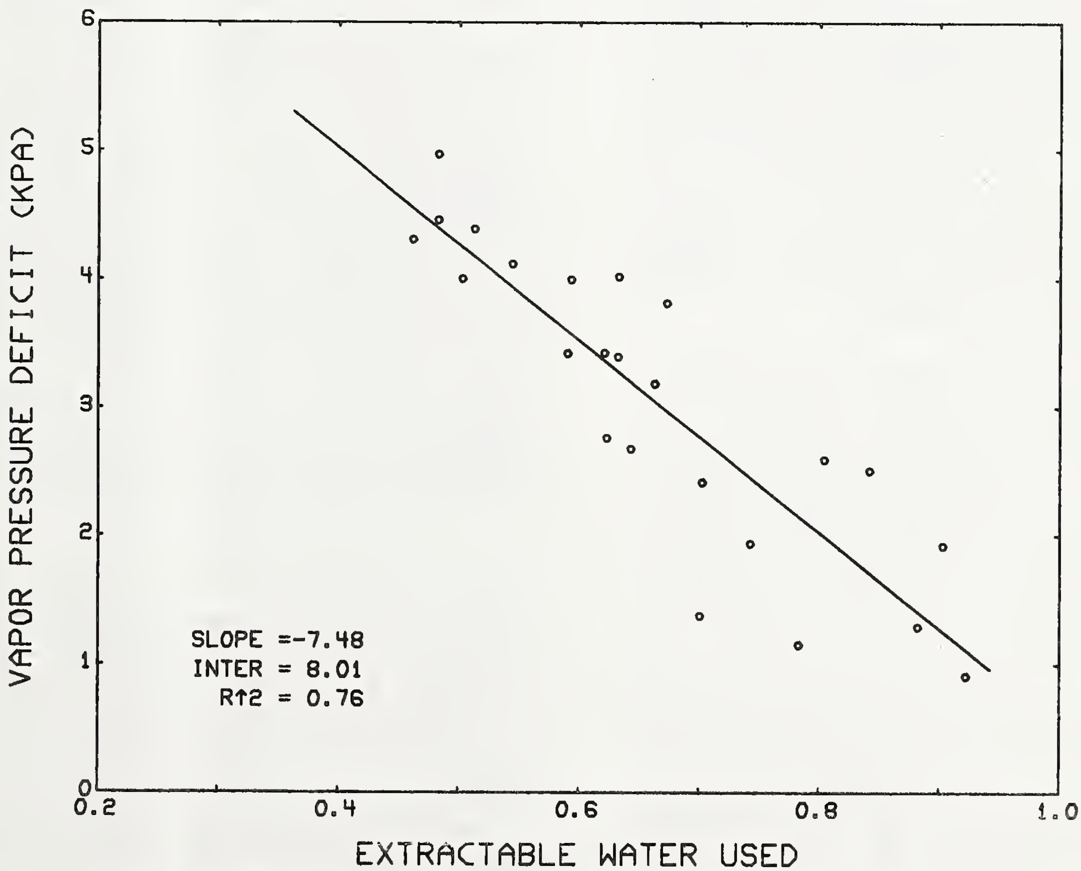

Figure 6. The vapor pressure deficit above which potential transpiration in cotton cannot be maintained vs. the fraction of extractable water used from the crop's root zone.

within hours. These results show that a unique relation between the CWSI and soil water content does not exist for all times. One explanation for the nonuniqueness is that, when stressed plants are irrigated, several days may be required for the plants to rehydrate and grow new root hairs. This recovery period is longer the more severe the stress to which the plants are subjected to (Reginato, 1983).

CANOPY TEMPERATURE AND EVAPOTRANSPIRATION

Canopy temperatures play a major role in evapotranspiration and can, therefore, be used in its estimation. Jackson et al. (1977) calculated evapotranspiration (ET) rates using canopy temperatures and compared the results with ET measured by weighing lysimeters and by soil water depletion. They proposed a simple empirical relation between $ET - R_n$ and $T_c - T_A$. A simplified approach such as this has the advantage that neither extensive ground measurements nor the evaluation of surface roughness is necessary.

Seguin and Petit (1980) calculated ET for a dry and an irrigated zone in southern France using four methods, two of which used remotely sensed surface temperature as an input. One of the methods was the simplified canopy temperature approach of Jackson et al. (1977). They concluded that the remote sensing methods gave satisfactory results, with a precision of 10% to 15% compared to an energy balance referenced method. Later, Seguin and Itier (1983) presented a detailed analysis of the approach of Jackson et al. (1977) and concluded that it was in agreement with theoretical analysis and that it can be considered a valuable first step for ET estimation using thermal-IR data from satellites.

Jackson et al. (1977) and Seguin and Itier (1983) discussed the estimation of daily totals of ET from one-time-of-day measurements. Jackson et al. (1983) developed a technique for making this conversion using time-of-day, day-of-year, and latitude information. They showed that, for cloudless days, the one-time measurement adequately predicted the daily value.

Hatfield et al. (1983) compared ET values calculated using surface temperatures and measured net radiation with ET obtained from weighing lysimeters. They concluded that, if buoyancy effects were accounted for, ET could be adequately estimated using surface temperatures.

STRESS-YIELD RELATIONSHIPS

A key element in most crop yield models is the prediction of the severity and duration of stress. Remote sensing techniques are well suited for monitoring both factors. Since the initiation of the ARS Wheat Yield Project, a major goal of our research has been to relate remotely sensed stress indicators to yield. Our first effort was to relate albedo, the ratio of reflected to incoming radiation as measured with a wide band (0.28 to 2.8 m) radiometer, to yield (Idso et al., 1977).

Measurements over Produra wheat (*Triticum durum* Desf. var. Produra) revealed a steady decline in normalized (to remove effects of changing sun altitude) crop albedo as the season progressed and the plant canopy became more dense. Initially this decrease in albedo was due to the proliferation of leaves and an increase in the amount of plant material that covered the otherwise bright soil surface. The albedo values decreased to a minimum, followed by an abrupt increase in canopy bright-

ness as the plants senesced. The minimum values were inversely correlated with the irrigation amounts supplied to the experimental plots and also with the final yield of grain.

Crop senescence rates

In the previous study it was obvious that albedo increased dramatically as grain began to ripen and plant leaves and stems senesced. Qualitative observations suggested that the rate of senescence was related to yield, with the senescence period being prolonged for plots that were stressed for water and ultimately produced the lowest yields. This hypothesis was verified experimentally by almost daily measurement of canopy spectral reflectance with a hand-held radiometer (Idso et al., 1980a). This instrument measured radiance in wavebands similar to the Landsat MSS (band 4, 0.5-0.6 μm; band 5, 0.6-0.7 μm; band 6, 0.7-0,8 μm; and band 7, 0.8-1.1 μm). The investigation spanned two growing seasons and included three crops; Produra wheat (*T. durum*), Anza wheat (*T. aestivum* L. var. Anza), and Briggs barley (*Hordium vulgare* L. var. Briggs), each of which was subjected to different irrigation treatments. The spectral reflectance index used was the transformed normalized difference between the red and one of the near-IR wavebands, i.e.,

$$\text{TVI-6} = \frac{\text{Band 7} - \text{Band 5}}{\text{Band 7} + \text{Band 5}} + 0.5^{1/2} \quad (4)$$

The first step in the analysis was to plot mid- to late-season trends of TVI-6 for each experimental plot and then by means of a sliding cubic curve fitting technique similar to that of DuChateau et al. (1972), calculate the average slope during the period of senescence (Idso et al., 1980a). Figure 7 shows that the slopes were inversely correlated with final yield in all three species of small grain. These results imply that the use of relative rates of senescence may prove to be a viable remote sensing technique for predicting yields in annual determinant plants such as small grains.

Multidate spectral reflectance

A third example of using reflected solar radiation in yield relationships includes a technique which monitors the trend in a spectrally-based vegetation index with time during the period of grain filling in wheat. This approach resembles that of using leaf area duration (the integral of green LAI with respect to time over the interval from heading until maturity) as a predictor of yield. An inherent limitation to the application of the leaf area duration method, however, has been the inability to make leaf area measurements frequently enough and with sufficient precision. Certain spectral vegetation indices, which are responsive to the photosynthetically active phytomass of the canopy, do not suffer the same limitations and can be substituted in lieu of LAI for yield prediction. Using this approach, Pinter et al. (1981) showed a relationship between final yield and the integral of a modified spectral vegetation index over the grain filling period. The relationship (Figure 8) accounted for 88% of the variability in yield from experimental field plots of Produra wheat. The range of yields due to different soil water levels was 103 to 656 g/m^2. Furthermore, this simple model worked equally well in predicting yields over two consecutive seasons despite differences in planting dates, planting densities and winter rainfall. Figure 8 also shows that data acquired from Anza wheat and Briggs barley were consistent with findings for Produra wheat. The

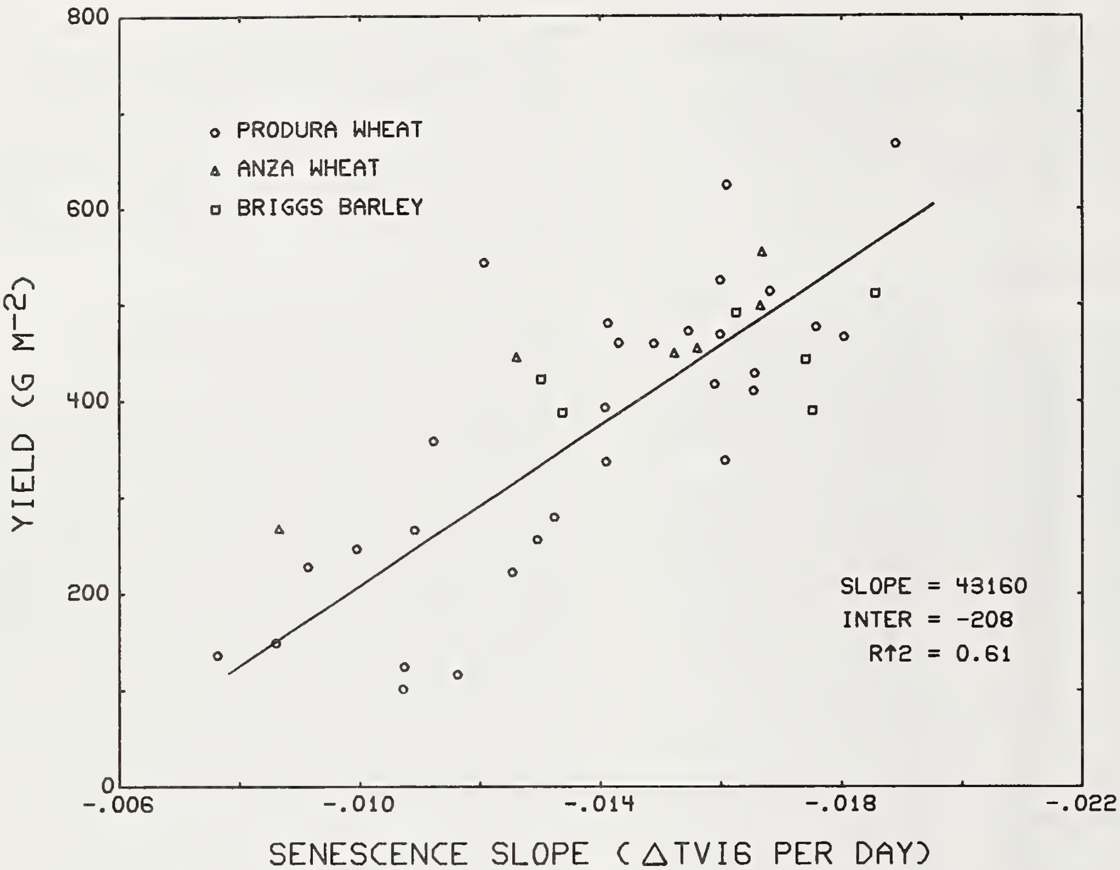

Figure 7. Final grain yield of Produra wheat, Anza wheat, and Briggs barley vs. senescence rate.

strength of a multi-temporal approach to yield estimation over that confined to a single data acquisition lies in its ability to compensate for staggered planting dates, and the improved predictive capabilities in regions where climates are variable.

Plant canopy temperature

There are various ways in which the final yield of a crop may be predicted from knowledge of plant canopy temperatures. Our first approach was based on the observation that water stressed wheat plants typically had radiant temperatures several degrees above the ambient air temperature. Temperatures of well-watered wheat, on the other hand, were often 3 to 5 C or more below air temperature. It followed that an accumulation of the daily plant temperature departure from air temperature, i.e., the SDD would reflect the history of the stresses to which the plants had been exposed. Further, we postulated that yield (Y) was inversely related to the SDD's accumulated during the heading period in wheat,

$$Y = \alpha - \beta \sum_{b}^{e} SDD_i$$

The term b represented the day on which the plants headed and e, the day when plants began to senesce, and α and β

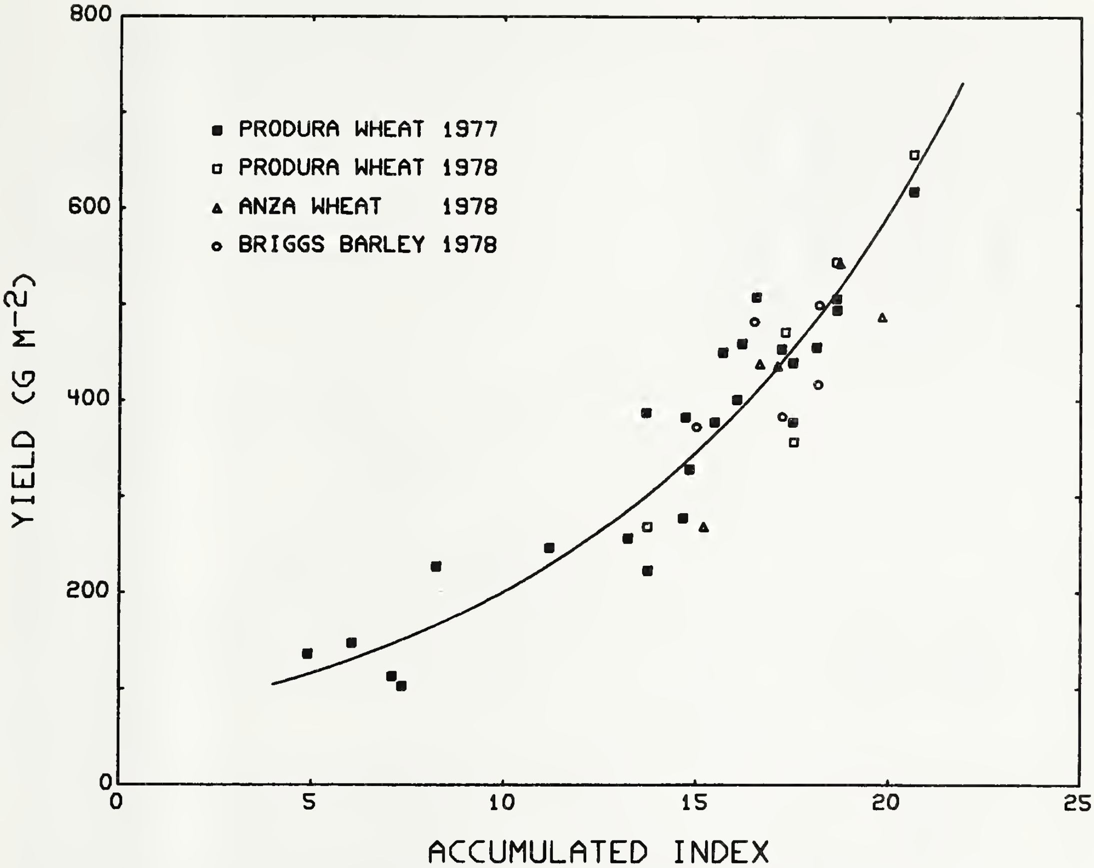

Figure 8. Grain yield (dry weight) vs. the accumulated daily values of a vegetation index from heading until senescence. The curvilinear relation was calculated for 29 Produra wheat fields.

are regression coefficients. Figure 9 (Idso et al., 1977) portrays the data for this relationship for Produra wheat grown in Phoenix in 1976. Low productivity is clearly associated with high SDD values and higher yields occur where lower SDD values imply high transpiration rates.

The next refinement was a "normalization" procedure to account for variability in growing degree days and the duration of daylight hours during the vegetation period of a crop's growth (Idso et al., 1979). The rationale for such a normalization was that pre-heading climatic conditions establish a potential for yield upon which post-heading growing conditions act to determine a final yield. Such a normalization worked well to bring together an apparent discrepancy between the results of yield data from two years of Produra wheat grown in Phoenix and one year of data from Davis, California where the pre-heading growing conditions were quite different (Idso et al., 1979).

In another approach, yields (normalized for solar radiation reception during the crop's vegetative growth stage) were related to the summation of stress degree days accumulated over the crops reproductive growth stage. This procedure brought the second wheat species (Anza) and the Briggs barley (both crops grown in two locations) into the

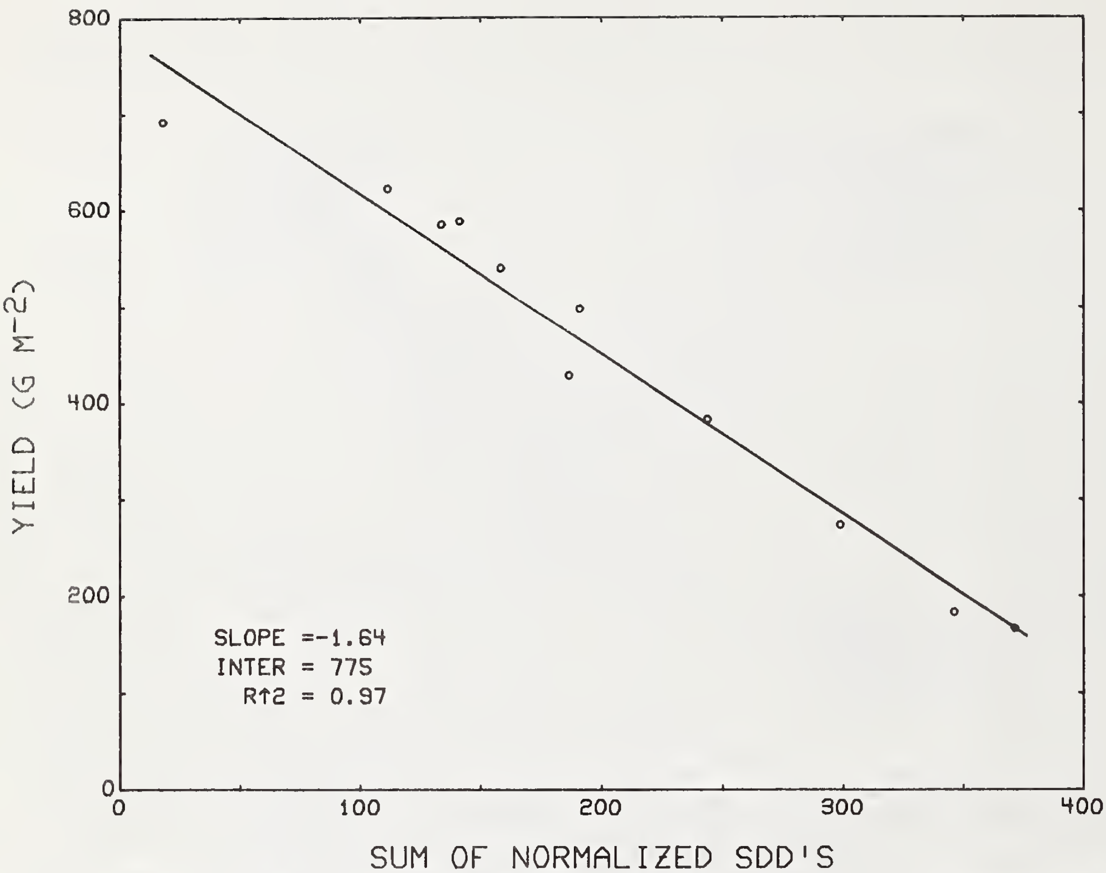

Figure 9. Algebraic sum of normalized SDD's from day 100 to conclusion of head growth (°C day).

relationship. Out of curiosity, the procedure was also applied to yield data obtained from four other crops grown at the different locations: red kidney beans, alfalfa, soybeans, and sorghum. The results were somewhat unexpected in that all the data fell within a single broad relationship (Figure 10). These results were especially significant from the point of view that plant stress operates to reduce yield from a potential level already established by previous conditions.

An important step in making yield models less sensitive to the effects of regional climate was made possible by substituting the more recently developed CWSI for the SDD in the accumulations. Idso et al., (1981c) showed that final grain yield was directly related to the average daily value of the CWSI observed during the grain filling period of Produra wheat. Later, in an approach designed to put the model on a more general basis, Idso (1984) converted the wheat yields to values relative to the maximum possible and graphed them versus the CWSI (Figure 11). That figure also included relative cotton yield and CWSI data from Pinter et al., (1983b). This plot of maximum harvestable yield appears to be a reasonably linear function of the CWSI, much like the net photosynthesis results (Idso et al. 1982b). Whereas net photosynthesis did not decline to zero until an index value of about 0.9 was reached, the linear extrapolation

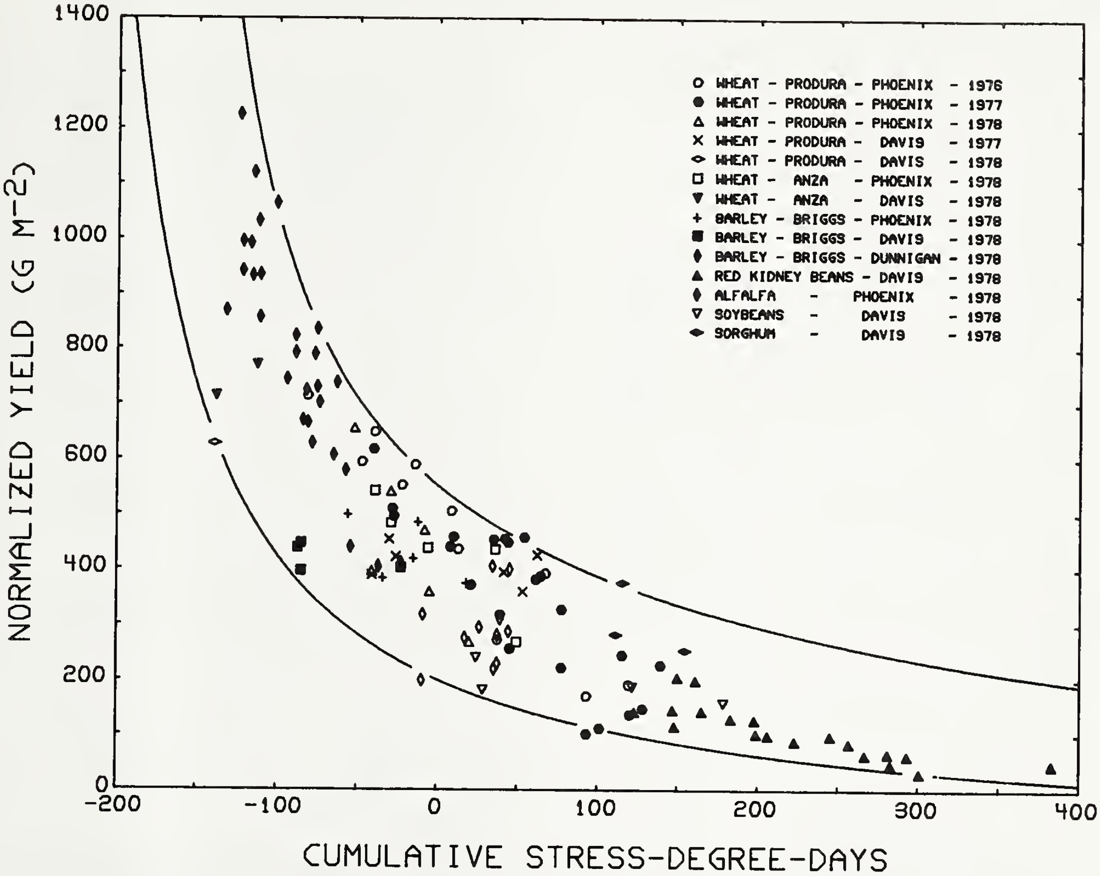

Figure 10. Crop yield as normalized for the total receipt of solar radiation during the vegetative period of growth vs. the summation of stress-degree-days accumulated during the reproductive period of growth. Normalized yield = yield (gm^{-2}) x 24,800 (cal cm^{-2})/Σ solar radiation.

of the final yield relationship in Figure 11 implies that a CWSI greater that 0.6 in cotton and wheat would probably not result in a harvestable yield.

Combination reflectance and temperature approach

It is important to emphasize that a combined multispectral approach will likely be necessary to achieve optimum yield prediction under a wide range of environmental conditions. In this way it would be possible to exploit different regions of the spectrum to identify not only the onset, distribution and intensity of stress in time and space, but also to reveal the potential productivity of the crop involved. The reflected portion of the spectrum (i.e., a vegetation index such as the normalized difference) may represent the plant's integration of past stress events and may provide information on potential productivity. In contrast, thermal infrared measurements are useful for assessing the current physiological status of the plants via the increase in tissue temperature which accompanies a reduction in evapotranspiration.

Changes in spectral reflectance which

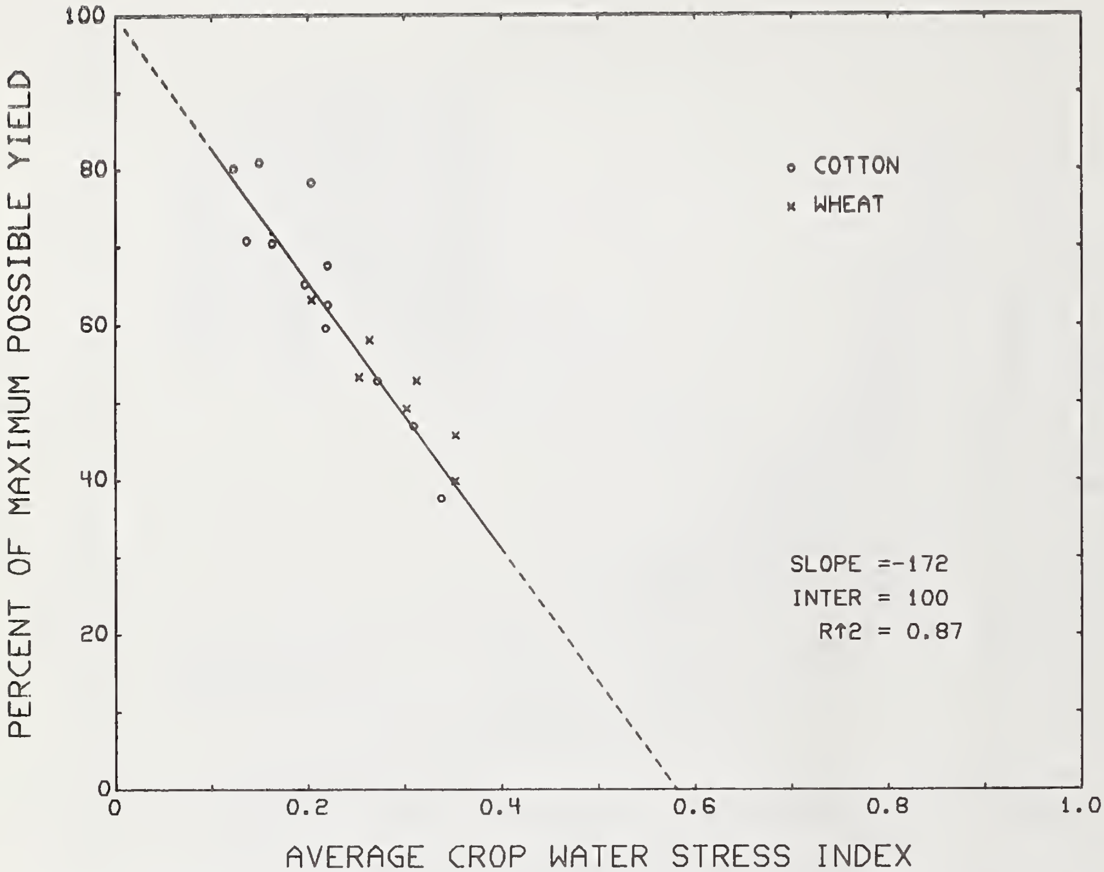

Figure 11. Final harvestable yield of cotton and wheat expressed as the percent of maximum possible yield vs. the average value of the plant water stress index over the period of yield development.

accompany architectural alteration of the canopy such as leaf wilting and curling can be monitored via traditional vegetation indices. The diurnal trend in reflectances of wheat can provide information on the vertical distribution of green elements within a canopy (Pinter et al. 1983a) or reveal the presence of morning dew on the canopy surface (Pinter and Jackson, 1981). The thermal infrared technique is sensitive to varying proportions of live and senescent tissue within its field of view.

Two techniques have recently been developed for merging the reflected and emitted portions of the spectrum into a comprehensive model which is capable of reasonably accurate yield prediction. Both techniques build upon the methods already discussed. The first deals with a problem inherent in using the thermal IR for yield prediction in alfalfa but can be applied to any case where ground cover is incomplete and the infrared thermometer views a composite temperature from both soil and plant components. Early in the harvest cycle when the canopy is sparse, temperatures are inflated due to the influence of the warmer temperature of the soil background. As a consequence the plant water status inferred from a CWSI calculation is likely to be grossly underestimated. In fact, alfalfa with a CWSI = 1 during this period can still be growing at moderate

rates of 5 to 10 g m^{-2} day^{-1} on a dry weight basis. Later, with the canopy more developed, these same growth rates can only be achieved when the CWSI is in the range of 0.0 to 0.5. These observations led to the development of an algorithm which predicts daily growth rates from a knowledge of canopy reflectance in the visible and near-IR, canopy CWSI values and green phytomass. It is portrayed graphically in Figure 12 (Pinter, 1983). The curved lines represent rates of growth which can be expected under various combinations of plant vegetation index values and CWSI. The data show that midway into the regrowth period the CWSI must exceed 1.75 before canopy growth will cease. Late in the cycle the canopy stops growing when the CWSI approaches 1.0. A value of zero for the CWSI at this time translates into a growth rate of about 10 g m^{-2} day^{-1}. Rising CWSI's associated with the growth isopleths from a vegetation index of 3 to 7 are explained by the drying soil conditions following harvest which caused apparent temperatures to increase markedly for several days. The algorithm provides a means to redefine levels of CWSI associated with acceptable levels of production in a dynamically changing perennial crop. Similar techniques should be appropriate for establishing the relationships between the CWSI and vegetative growth and intermediate yield components of annual crops such as wheat.

Recently, Hatfield (1983) suggested that spectral reflectance measurements be used to define the starting and ending times for a stress-degree-day summation period in sorghum and wheat, obviating the requirement for precise ground truth estimates of phenological events previously required. In addition, he proposed that a vegetation index be used to estimate the potential harvestable yield at the onset of the

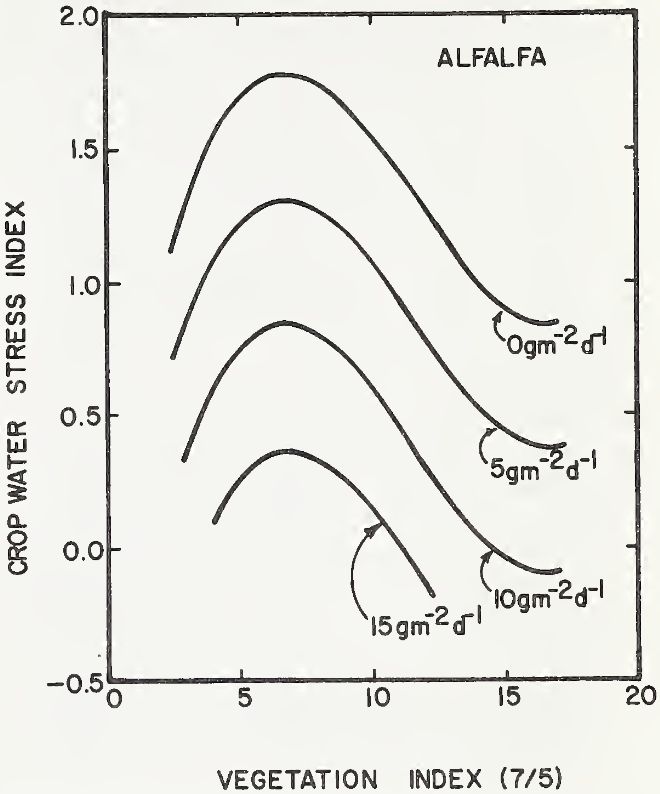

Figure 12. CWSI values associated with different rates of green alfalfa canopy growth (g m^{-2} day^{-1}) under various canopy density conditions during the summer in Phoenix, AZ.

heading/grain filling period. The stress-degree-days could then be used to estimate the yield from the potential to reflect the intensity of stress following heading. Thus, this technique provides a method to generalize the SDD accumulation approach to yield modeling to include a wide range of canopy densities (i.e., potential yield) at the onset of the critical grain filling period.

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245

CHAPTER 7. DESCRIPTION OF MSS DATA

L. F. Lautenschlager[1]

INTRODUCTION

Multispectral scanner (MSS) data, obtained form a series of earth resources technology satellites (Landsat 1, 2, 3 and 4), were collected at twenty ARS wheat yield study sites. The Landsat multispectral scanner sensor system measures reflectance of a scene in four wavelength intervals, commonly referred to as bands or channels, in the visible and near-infrared portion of the spectrum in the range of 0.50 um to 1.10 um.

An extensive discussion of reflectance properties is provided by Jackson, et al. (1980), Tucker and Miller (1977) and Deering, et al. (1975). The sensor measurements are influenced by the vegetation canopy, soil type, soil moisture and atmospheric conditions.

The spectral measurements have been used by investigators for qualitative and quantitative assessment of plant canopies. Generally, they have reduced the four bands of data down to a single number for assessing various canopy characteristics such as leaf area, biomass, percent ground cover and plant population [Pearson and Miller (1972) and Wiegand et al. (1974)]. The formulae used to reduce MSS data have become known as vegetation indices. Some investigators, Wiegand, et al. (1974), Seevers, et al. (1973), and Tucker (1979) have used the individual bands to assess canopy characteristics.

Lautenschlager and Perry (1981) provide a comprehensive comparison of vegetation indices. They concluded that many vegetation indices are very similar. Some vegetation indices, in fact, can be shown to be algebraic transforms of others (Perry and Lautenschlager (1984)).

DATA COLLECTION

The MSS spectral data were collected to test correlations against the ground truth collected by ARS scientists on specific wheat fields and by the Statistical Reporting Service (SRS) enumerators on a number of surrounding fields. The data collected by the ARS scientists are described in Chapter 2. The data collected by SRS were not as detailed as that collected by ARS but covered other crops in the immediate area. All fields within a predetermined area were inventoried. Periodic observations were made on barley, rice, sunflowers, rye, corn, sorghum, wheat, cotton, soybeans, and oats. The initial interview collected data on acreage, planting date, emergence date, seeding rate, previous use, fertilizer, pesticides, row direction, row width and variety. Periodic observations were made weekly; the data collected were plant height, ground cover, canopy color, growth stage, surface moisture, weediness, disease damage, insect damage, hail damage and lodging. The final interview determined acreage harvested, harvest date, production, moisture content, harvest method, fertilizer and irrigation. Precipitation measurements were collected daily by cooperating farmers. The data collected in 1979 consisted only of field inventories. Table 1 shows the number of fields by crop over which periodic observations were made in 1980 and 1981.

[1] Mathematical Statistician, Statistical Reporting Service (SRS), U.S. Department of Agriculture (USDA), Johnson Space Center, SC2, Houston, TX 77058.

Table 1. Number of fields for which SRS made periodic observations by crop, segment and year.

SEGMENT	YEAR	CORN	COTTON	DURUM	OATS	SORGHUM	SPRING WHEAT	SUNFLOWERS	WINTER WHEAT
819	80				1		4		
819	81			2			4		
946	80								3
946	81								4
947	80								8
947	81								6
948	80								4
948	81								6
949	80		5						7
949	81		5						10
950	80	2				5		2	10
950	81	1				11			18
994	80								10
995	80	4							6
996	80								10
996	81								10
997	80								10
1465	80			9			1	3	
1465	81			9			1	4	
1471	80			6			4	2	
1471	81			2			8	5	
1540	81						3		
1577	80	1			2		8	2	
1577	81			3			2	3	
1943	81			3			7	3	
1988	80								10
		8	10	34	3	16	42	24	132

MSS DATA HANDLING

The field boundaries were digitized from aerial photographs and plotted on translucent paper. MSS data were computer converted to hard copy computer printouts (grey scales) at the same scale as the digitized boundaries were plotted. The field outlines or plots were then overlaid on the greyscales to register the MSS data to the field boundaries and the MSS data was extracted. The means for all four channels of data along with the number of pixels and sums of squares were computed for each field. These data were computed first using only pure field pixels and then recomputed including border pixels. These basic data will allow the computation of other required statistics.

MSS DATA ACQUISITIONS

About 510 acquisitions of data were put together for the 20 locations. Table 2 shows the breakdown by location by crop year as to the approximate number of acquisitions acquired. These totals include clear images and some partially cloud covered scenes. A large number of images were screened at the EROS data center at Sioux Falls which indicates there are other cloud free acquisitions. Crop year is defined as planting to harvest. The crop year for spring wheat locations was considered to be May through September. For the winter wheat locations it was considered to be September through August. These time periods could probably be narrowed further for wheat but may not be long enough for other crops.

Table 3 shows the number of fields by crop, year, and site for which MSS data are available. Segments 994-999 and 1988 each had one winter wheat field in 1977-78 for which MSS data are available but are not included in Table 3. Other crops in Table 3 include a few fields each of dry peas, dry beans, safflower, millet, rye, soybeans, barley and flax. Grass includes pastures that were grazed and idle grasslands.

The spectral data, along with SRS data described earlier in this chapter, the ARS field data as described in Chapter 2 and the instrumented climatic data as described in Chapters 3 and 4 will be put into data files and stored on tape. SRS will have control of those data files but can be made available to anybody who is interested in doing any data analysis.

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Table 2. Summary of the number of MSS Landsat acquisitions obtained over the 20 ARS wheat yield study sites by crop year. Crop year is defined for spring wheat as May through September and for winter wheat from September through August. Spring wheat was grown at all North Dakota sites and for 1979 in Montana.

STATE	COUNTY	TOWN	OPERATOR	SEGMENT	1978	1979	1980	1981	1982
Colorado	Washington	Akron	Site 1	996	7	8	8	18	6
Kansas	Finney	Garden City	Site 3	1988	15	10	11		
Kansas	Greeley	Tribune	Site 2	997	10	0	12		
Kansas	Jewel	Mankato	Site 7	998	4	1			
Montana	Richland	Sidney	Rasmussen	1540		14		13	
Montana	Richland	Sidney	Zoanni	1540			6		
Montana	Sheridan	Froid	McCabe	1943		10			
Montana	Richland	Culbertson	Daniels	1943			9		
Montana	Roosevelt	Froid	Deubner	1943				12	
Nebraska	Banner	Albin, WY.	Site 5	995	13	8	9		
Nebraska	Keith	Paxton	Site 6	994	5		8		
Nebraska	Perkins	Paxton	Site 6	994		3			
North Dakota	Burleigh	Wing	Thorson	819		8	10	13	
North Dakota	McKenzie	Alexander	Heinz	1627		6			
North Dakota	McClean	Turtle Lake	Birst	1628		6			
North Dakota	Nelson	Lakota	Marquart	1465		13	7	5	
North Dakota	Sheridan	Goodrich	Winter	1577		7	1	9	
North Dakota	Wells	Bremen	Ystaas	1471		4	6	5	
Oklahoma	Grant	Medford	Site 4	999	10	4			
Oregon	Morrow	Ione	Martin	946		17	4	15	4
Oregon	Sherman	Moro	Burnett	947		17	10	21	3
Oregon	Umatilla	Pendleton	Spratling	948		4	7	12	2
Texas	Randall	Bushland	ARS Farm	950		3	4	11	
Texas	Wilbarger	Vernon	Lowe	949		14	9		
Texas	Wilbarger	Vernon	Byers	949				18	

Table 3. Number of fields for which Landsat MSS data have been extracted by crop year and location.

SEG	YEAR	ALF HAY	CORN	COT	DURUM	GRASS	FALLOW	OATS	OTHER HAY	OTHER CROPS	SORG.	SUN-FLOWER	SPRING WHEAT	WINTER WHEAT	WASTE
819	1979	6				9	19	9	4				29		3
819	1980	4				17	7	2	2				8		6
819	1981	4			2	8	11	5	3	3			15		6
946	1979						8						2	23	24
946	1980						4							3	3
946	1981						3							4	3
947	1979						19						2	14	4
947	1980						5						1	8	4
947	1981						10							7	4
948	1979	1				3	46			6				65	17
948	1980						11							6	
948	1981						7							11	1
949	1979			9		1								20	6
949	1980			13		1								16	5
949	1981			7		1	6							20	5
950	1979		2			1	9		2		6	1		10	6
950	1980		3				9		1		7	2		12	4
950	1981		3			12	8	2		2	56	1		83	
994	1979	1				3	38	1						36	5
994	1980						39							38	4
995	1979		8			1	11	2	1					8	1
995	1980		4				10			3				12	2
996	1979					2	12			3				13	7
996	1980	1					20							12	5
996	1981						14							17	3
997	1979					4	8			2	1			14	1
997	1980					3	18				2			13	3
998	1979					6	1				10			20	9
999	1979					11	1		7					14	10
1465	1979				12	1	11			2		6			21
1465	1980				18		8			1		4	1		13
1465	1981				12		7	1				5	1		14

Table 3. (continued) Number of fields for which Landsat MSS data have been extracted by crop year and location.

SEG	YEAR	ALF HAY	CORN	COT	DURUM	GRASS	FALLOW	OATS	OTHER HAY	OTHER CROPS	SORG.	SUN- FLOWER	SPRING WHEAT	WINTER WHEAT	WASTE
1471	1979	1			5	8	4	2	6	7		9	15		12
1471	1980				9	2	9		3	2		5	13		7
1471	1981				4	1	5	1	1	1		14	10		10
1540	1979						14	1		3			20		9
1540	1980	3	1			4	15	3	1	1			7	3	7
1540	1981	4	1		6	6	23	2	1	2			9	6	4
1577	1979				8	7	11	3	5	2		1	7		45
1577	1980		1			3	12	6	1			5	9		20
1577	1981		1		6	4	8	5	5			5	8		16
1627	1979				5	4	32	5	6				29		7
1628	1979				8	7	44	13	3	4			49		15
1943	1979	1			5	1	23	1		4			19		6
1943	1980	1				6	23			3			22	2	7
1943	1981				6	1	19			2		3	12	4	4
1988	1979						10				1			20	4
1988	1980						12							14	
		27	24	29	106	138	644	64	52	55	83	61	288	548	372

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245

CHAPTER 8. PHYSIOLOGICAL AND PHENOLOGICAL RESEARCH IN SUPPORT OF WHEAT YIELD MODELING

Betty Klepper, A. B. Frank, A. Bauer and J. A. Morgan[1]

INTRODUCTION

Any process-oriented plant yield modeling effort must have strong support in field-based plant physiology because the final arbiter of dry matter production and allocation is the plant. The most dynamic component in any agricultural model, the plant changes in size on a daily scale and in water status and canopy temperature on a scale of minutes. Therefore, any dynamic model of wheat yield must be based on a thorough understanding of production processes and their sensitivity to environmental conditions. To permit generalization across many different environmental regimes, physiological research has had to take fundamental, rather than applied, approaches.

The areas of physiological research undertaken in support of the ARS wheat yield modeling program have been primarily limited to aspects considered critical to model development. Of particular concern have been emergence and stand establishment, plant developmental morphology, plant water relations and gas exchange of shoots. Work in each of these areas has typically proceeded at two or three locations with different climates, soils, cultivars, and agronomic practices so that results could be compared to determine their generality.

EMERGENCE AND STAND ESTABLISHMENT

Establishment of an adequate seedling population is critical to production in any crop, but is especially important for dryland winter cereals where deep seeding is often required to reach soil water for germination. With deep planting (more than 5 cm), emergence is delayed and post-plant rains may cause crusting (Lindstrom et al., 1976).

For shallow (3 to 4 cm) plantings into moist, friable seedbeds, use of a growing-degree-day (GDD) model predicts emergence. GDD for any time interval are calculated from the summation of

$$\frac{T_{max} + T_{min}}{2} - T_b$$

for each day in the interval. T_{max} and T_{min} are maximum and minimum air temperatures, respectively, and T_b is a base temperature for the process. Soft white winter wheats seeded 4 to 9 cm deep near Pendleton, Oregon require 100 GDD (T_b = 3C) for 50% emergence (Rickman et al., 1983) and hard red and durum spring wheats, seeded at 4 cm depth in a clean surface seedbed, need 100 GDD (T_b = 0C) for full emergence (Bauer et al., 1984). If these GDD requirements had been calculated with the same base temperature and the same endpoint, the soft white winter wheats would probably still require more heat units to emerge than would the spring wheats because of differences in cultivar properties. Generally, winter wheats are planted deeper than spring wheats and the soft white wheats are slower to emerge than hard red wheats.

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For seedbeds with surface residues, nutrient deficiencies or suboptimal soil water, longer periods are required for emergence and a simple GDD model is inadequate. For example, in no-till seedbeds, drill opener design (Wilkins et al., 1982a, b) and fertilizer placement (Klepper et al., 1983a) are crucial to emergence and early seedling vigor. Without surface residues, spring wheats emerged about a day earlier than where residues were present (Bauer et al., 1984).

PLANT DEVELOPMENTAL MORPHOLOGY

Domestication, selection, and gene manipulation have extended wheat culture from its apparent Near East origin (Briggle, 1980) to areas of the globe bounded by the 60° latitudes. Such expansion was possible because the cultivars developed were adapted to a range of temperature and daylength regimes. Models must account for this range in environmental response.

Accumulated thermal units (GDD) are equal to or superior to other energy summation indices (Sastry and Chakravarty, 1982) or the poikilotherm equation (Kiniry and Keener, 1982) to predict development rate. Furthermore, calculation of GDD requires only air temperature which is easily measured and routinely available from weather stations.

Leaf and tiller development

Growing degree days can be used to time leaf and tiller development (Bauer et al., 1984; Rickman et al., 1984; Rickman, 1984). A system which assigns unique names to each leaf and tiller on a cereal plant has been used to follow winter wheat development under field and growth chamber conditions (Klepper et al., 1982; Klepper et al., 1983c). This system, a modification and extension of Haun's (1973) method, permits assessment of seedling vigor (Wilkins et al., 1982b) and seedbed adequacy (Wilkins et al., 1982a; Peterson et al., 1982).

Figure 1 shows the names of leaves and tillers on a wheat seedling. Using Haun's (1973) system of counting leaves, this plant has 4.4 leaves on the main stem, 2.5 leaves on T0, 1.8 leaves on T1, and 1.3 leaves on T2. The leaves on the tillers have two-digit designations and those on subtillers require three digits. Each tiller is named for the leaf which subtends it; for example, T1 is in the axil of L1, T10 is in the axil of the prophyll on T1 and T12 is in the axil of the second leaf on T1.

Growth chamber work (Klepper et al., 1982) has shown that each leaf on the plant requires the same number of days to elongate in any given environment. This time-interval, a phyllochron, can be measured in the field by GDD.

For winter wheats at Pendleton, Oregon, there are 80 to 110 GDD ($T_b = 0$) per phyllochron with much of the variation resulting from planting date; earlier fall planting dates give seedlings which require more GDD's per phyllochron (Rickman, 1984). Under semitropical conditions, values can range from 84 to 198 depending on cultivar and season with a rise in the number of heat units per leaf for the later leaves (Wiegand et al., 1981). Spring wheats require 73 to 81 GDD per phyllochron in North Dakota, and soil water and fertilizer N rate did not affect this development rate (Bauer et al., 1984).

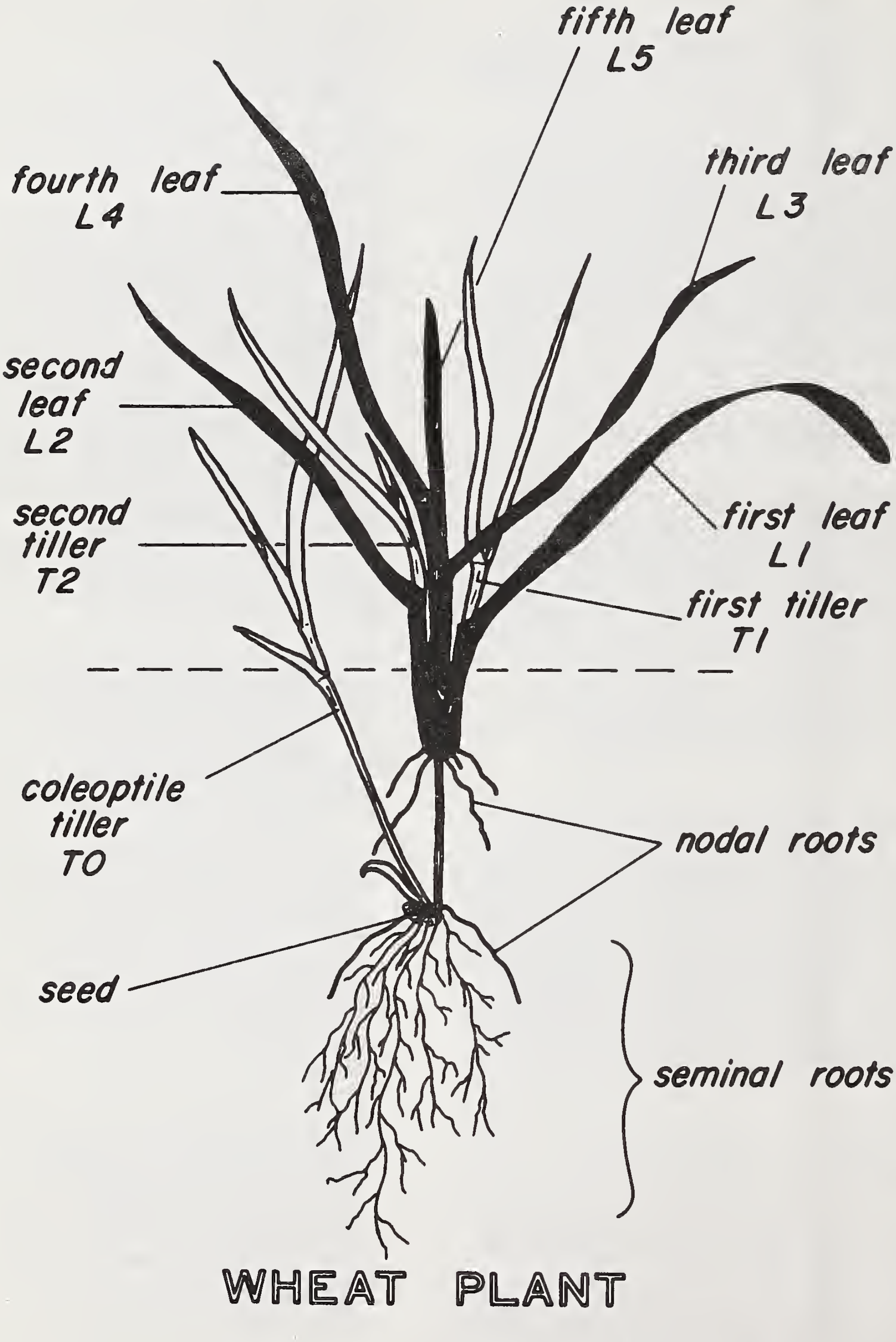

Figure 1. A wheat plant with named leaves and tillers for the main stem. Subtillers have two-digits designations (Klepper et al., 1982).

Inflorescence development

The shoot apex produces vegetative (leaf) primordia during early plant development. The apex then elongates and produces a series of single ridges. After several single ridges are present on the elongated apex, the second ridges (which will become spikelets) appear and form the "double ridge" stage. Then further spikelets are formed until the terminal spikelet appears.

A numerical index for scoring spike development (Klepper et al., 1983b) has been used on winter wheats in Colorado to show that neither water stress nor competition from high seeding rates affects the rate of development of the spike (Dunbar, 1982).

For spring wheats, events are telescoped into short periods. During the vegetative stage of apex development, spring wheats rapidly increase leaf area, dry matter, and tiller number. Under North Dakota conditions, the main stem apex of spring wheat changes from vegetative to reproductive 14 to 21 days after emergence (Frank and Bauer, 1982). The time required to reach double ridge stage differs for different cultivars whether measured by days from emergence, accumulated GDD, or Haun (1973) stage of main stem development (Table 1) (Frank and Bauer, 1984). Cultivars differ in duration of the vegetative stage of apex development by as much as 3.7 days. To reach double ridge, durum cultivars took longer, required more GDD's and had greater Haun scores than did hard red spring wheats; they also had higher grain yields.

Although temperature affects the timing of double ridge formation in spring wheat, available soil nitrogen does not (Frank and Bauer, 1982). In growth chamber experiments, duration of the apex vegetative phase of Sinton spring wheat decreased significantly as temperature increased from 10 to 26°C (Table 2). Apices of mainstems reached double ridge sooner than those of tillers; however, all tillers formed double ridges at about the same time and took 2 to 3 days longer than the main stem to do so. Figure 2 shows beneficial effects of high soil nitrogen and low ambient temperature. Kernel numbers are reduced as soil nitrogen decreases and ambient temperature increases. The adverse effect of high temperature could not be alleviated by applying fertilizer nitrogen. Under field conditions, apex development was influenced much less by treatment differences in available nitrogen and water than by cultivar differences (Frank and Bauer, 1984).

Both the rate of inflorescence development and the final spikelet number can be affected by cultivar and by environmental factors (Rawson, 1971; Rahman et al., 1977; Rahman and Wilson, 1978). For example, five spring and five winter wheats, under growth chamber conditions, required fewer days from planting to heading at 21/12.7 C (day/night) than at 15.5/7.2 C (Pirasteh and Welsh, 1980). This reduction differed among cultivars within a class suggesting that each cultivar has a specific phenotypic response potential to temperature change. All cultivars used more degree-hours at the warmer temperature. The average difference of the five cultivars between classes was the same, indicating that once cold temperature requirements are fulfilled, obligate winter wheats respond with the same physiological dynamics as spring wheats.

In general, the number of growing-degree days (GDD) required by wheat from seeding to heading decreases with

Table 1. Days duration, accumulated GDD, and mean Haun at apex double ridge and grain yield of hard red spring and durum wheat culitvars (Frank and Bauer, 1984).

Cultivar	1980				1981			
	Double Ridge	GDD	Mean Haun	Grain Yield	Double Ridge	GDD	Mean Haun	Grain Yield
	Days			kg/ha	Days			kg/ha
Butte	14.3	176	3.8	612	18.7	232	3.6	2950
Coteau	18.0	244	4.3	873	20.3	258	3.8	2845
Lew	14.3	176	3.2	685	17.0	208	2.7	2836
Saratovskaya 29	16.0	203	3.7	649	20.7	266	3.6	2144
Waldron	15.7	197	3.6	421	18.0	221	3.3	2774
Len	15.3	191	3.5	808	19.7	247	3.6	2875
Cando†	18.7	260	4.3	1039	21.7	281	3.8	3497
Edmore†	18.0	244	4.2	872	21.7	281	3.6	2888
Vic†	18.7	258	4.5	901	22.7	290	3.9	3142
$LSD_{.05}$‡	0.9	17	0.2	134	1.8	25	0.3	639

† Durum wheats.
‡ LSD for cultivar means.

Table 2. Duration (days) of vegetative stage (from main stem emergence to double-ridge) for the M, T1 tiller, T2 tiller, and T3 tiller of Sinton spring wheat grown at three temperatures. Data are averaged across 0, 78, and 224 kg N/ha levels. F-value for N levels was not significant (Frank and Bauer, 1982).

Temperature	Order of Tiller				
	M	T1	T2	T3	Avg.
C	days				
10	24.1†	25.8	26.8	25.1	25.4‡
18	22.2	24.5	24.4	24.8	24.0
26	16.7	18.8	20.0	19.3	18.7
Avg.	21.0§	23.0	23.7	23.1	

†LSD (.05) Temperature x Tiller = 0.89 days.
‡LSD (.05) Temperature = 0.90 days.
§LSD (.05) Tiller = 0.62 days.

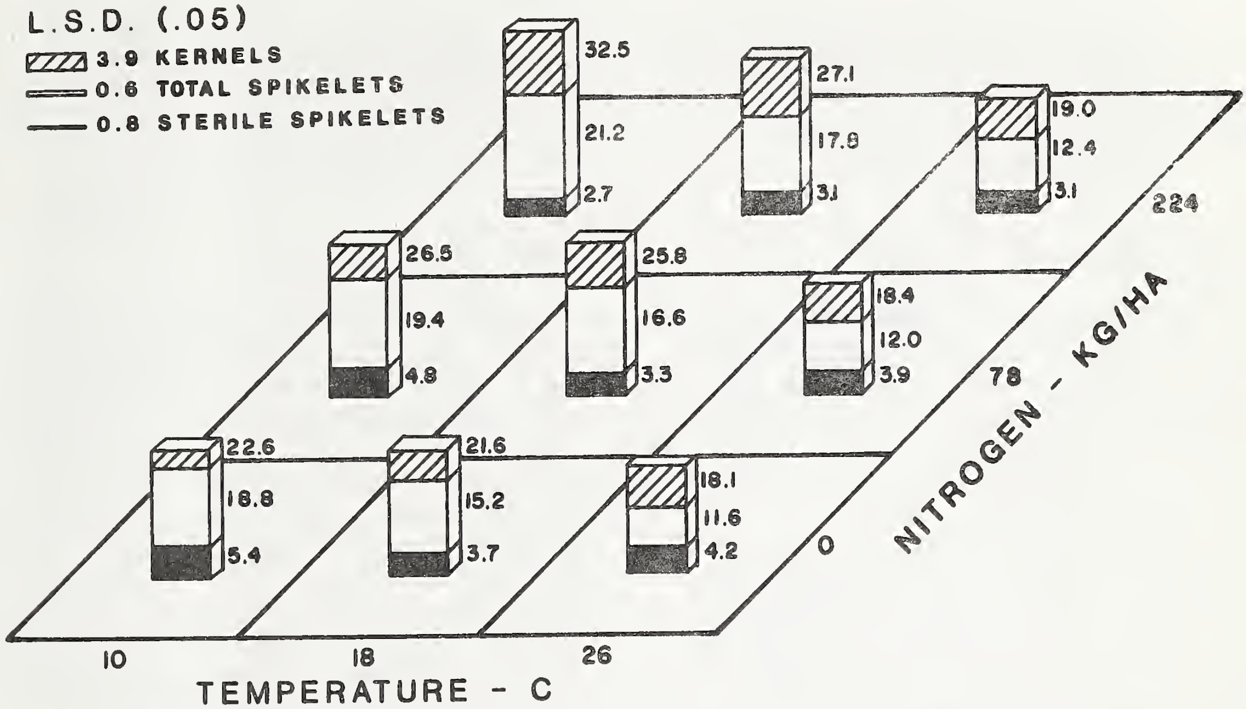

Figure 2. Number of spikelets (total and aborted) and the number of kernels produced by main stem and first three tillers of Sinton spring wheat grown at combinations of three N levels and three temperatures (Frank and Bauer, 1982).

increase in latitude (Peterson, 1965). This is primarily attributed to the greater number of daylight hours during the growing period at the higher latitudes. Nuttonson (1948) introduced the photothermal unit (PTU) concept -- defined as the product of daily GDD and daylight hours -- to provide a basis to account for wheat development differences due to latitude.

Bauer et al. (1984) showed that the number of GDD accumulated per leaf was the same in a 7-leaf cultivar as in 8-leaved cultivars of hard red spring wheat. However, because of the difference in number of leaves, the GDD accumulated from emergence to flag leaf was greater in the 8-leaved cultivars.

Some cultivars of both spring and winter wheats are sensitive to daylength, others are not. Rate of development of daylength sensitive cultivars will increase with lengthening photoperiod (Halse and Weir, 1970). Spring wheat cultivars, in general, are less sensitive to photoperiod than winter wheat (Pirasteh and Welsh, 1980). The threshold daylength at which photoperiod sensitivity is no longer expressed is not known. Dr. Richard Frohberg (Agronomy Department, North Dakota State University, personal communication) indicated that sensitivity in hard red spring wheats is expressed at photoperiods of 12 hours but not of 14 hours. For Australian wheats, expression of photosensitivity is uncommon in days with 10 or more hours of daylight (Halse and Weir, 1970).

Grain filling is also influenced by temperature, which apparently sets plant senescence, because temperatures in excess of about 15 C shorten the

duration of grain filling (Wiegand and Cuellar, 1981). Because of this decrease in duration, kernel weights tend to be proportional to filling rates with temperature stress.

Root Development

A healthy, vigorous, and deep root system is important for good grain production in dryland areas. Wheat has two root systems; seminal roots arise from primordia present in the seed and serve as the primary source of water and minerals until the seedling is well-established and begins to tiller. At early tillering, a crown root system appears on the main stem. In addition, each tiller develops its own root system when it has about three leaves (Klepper et al., 1984). All of the root axes on wheat plants can be associated with nodes which are in the seed, in the main stem, or in tillers or subtillers. A naming system permits the developmental history of roots associated with particular nodes to be studied. Roots are named for their associated nodes along with a letter to indicate their direction of growth. Figure 3 shows for wheat main stems the relationships among leaf, tiller, and root axis development. Seminal roots in Figure 3 have negative node numbers. Note that seedlings are supported primarily by seminal roots prior to tillering.

Tillers become independently rooted when they have about three leaves (Klepper et al., 1984) and the tillers of winter wheat which abort in late spring are generally the smallest ones which have not had sufficient time to develop roots. This observation is consistent with the fact that the number of root axes is a good predictor of the number of heads at harvest (Black, 1982) and with the fact that fall-produced tillers in winter wheat are more productive than spring-produced tillers with the percent of tillers surviving being positively correlated with yield (Shanahan, 1982).

GROWTH STAGE SCALES

A growth stage scale, through use of numeric or alphabetic designations, describes the status of plant development during its life cycle. Commonly used scales that describe the morphologic development of wheat are those of Feekes (Large, 1954), Robertson (1968), Haun (1973), Zadoks et al. (1974), and Waldren-Flowerday (1979) (Table 3). These scales differ in method of designation, with extent of morphological change effecting a change in designation, and with the number of kinds of morphological features considered as a basis for scale designation (Bauer et al., 1983). Morphological features usually considered are leaves, nodes, tillers, and various visible phases of the inflorescence.

The scales of Zadoks et al. and of Haun track leaf exsertion on the main stem, chronologically assigning each leaf a number as a scale designate. In contrast, the Feekes, Robertson, and Waldren-Flowerday scales disregard differences in the number of main stem leaves and base the designation primarily on appearance of nodes above ground and characteristics such as tillering.

Multiple designations employed by the Zadoks et al. scale provide greater descriptive detail during tillering and stem elongation than other scales. Advantages of detail during these stages probably accrue to a greater extent with winter wheat cultivars which tiller profusely, than with spring wheats which rarely produce as many as four tillers per plant. Spring

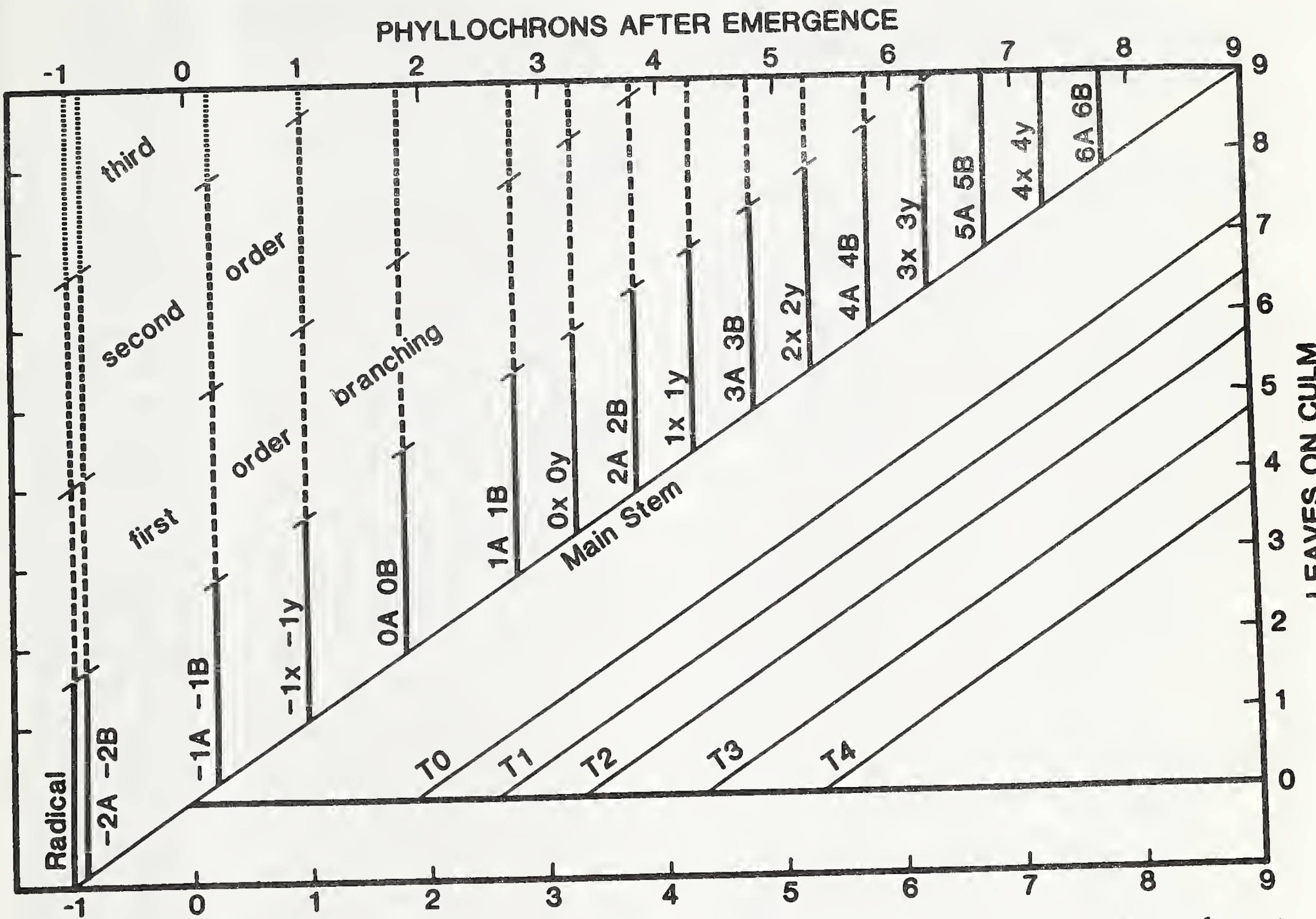

Figure 3. Relationships among main stem leaf number, tiller development, and root axis appearance and development for wheat (Klepper et al., 1984).

wheat seeding rates, about 250 viable seeds per m^2, normally exceed those of winter wheat by 40 to 50 percent.

In addition to scale flexibility, scale definitiveness also enhances the precision of estimation of growth stage from accumulation of GDD. As an example, differences in what constitutes "heading" in spring wheat can alter the time frame for this occurrence by several days and as much as 80 GDD. The Haun scale is the most definitive because the designations ascribed to each morphological unit are further subdivided into decimal fractions.

Thus, heading is designated in five stages from the time the awns appear through the collar of the flag leaf until the spike has completely cleared the collar. Further, the observations are made exclusively on the main stem, avoiding observations on tillers, which are synchronous with the main stem but lag in development stage.

Postanthesis growth stages are based on degree of hardness of the kernels. Because flowering begins in the center spikelets of the spike, degree of precision in designating postanthesis stages is governed by the uniformity in

Table 3. Correlation of five wheat growth stage scales[1] (Bauer et al., 1983).

Description	Robertson	Waldren-Flowerday	Zadoks-Chang-Konzak		Haun	Feekes
Planting			00			
germination	(P)					
Emergence	(E)	0	09		0.0	
				10	0.2	1
Seedling					0.4	
growth					0.6	
					0.8	
					1.0	
			11		1.2	
					1.4	
			12		1.6	
					1.8	
					2.0	
		1			2.2	
					2.4	
			13		2.6	
					2.8	
Tillering		1.5		20	3.0	2
					3.2	
					3.4	
			14[2]		3.6	3
					3.8	
					4.0	
					4.2	
					4.4	4
			15[2]		4.6	
					4.8	
		2			5.0	5
					5.2	
				30	5.4	
Stem	(J)	3	16[2]	31	5.6	6
extension					5.8	
					6.0	7
					6.2	
					6.4	
Stem			17[2]		6.6	
extension					6.8	
(continued)		4		37	7.0	8
					7.2	
					7.4	
			18[2]		7.6	
					7.8	
		4.5		39	8.0	9
Flag leaf				41	8.2	
extension					8.4	
					8.6	9
					8.8	
					9.0	
Boot		5		43	9.2	10
					9.4	
				45	9.6	
					9.8	
				47		
				49	10.0	
Heading	(H)	5		50	10.2	10.1
					10.4	
					10.6	
					10.8	
				59	11.0	10.5
Spike					11.2	
extension						
Anthesis		6		60	11.4	10.5.1
				65	11.5	10.5.2
					11.6	10.5.3
		7		69		10.5.4
Milk	(S)			71		
Dough		7.5		73-77		11.1
		8		83-85		11.2
		9		87-91		11.3
Ripe	(R)	10		92		11.4

[1]Based on 8 leaves on the main stem.
[2]Denotes number of leaves on the main stem and no tillers.

selection position from which kernels are removed for testing.

WATER RELATIONS IN WHEAT

Water stress is a common occurrence in most wheat growing areas of the world. This is especially true for the Great Plains of North America. The ability of wheat cultivars to maintain a high leaf water potential does not necessarily indicate drought tolerance. However, when considered along with yield, this ability does provide a relative index for comparing cultivars. Sojka et al. (1981) showed that cultivars of both T. aestivum and T. durum with lower seasonal leaf water potential had higher percent yield reductions. Leaf water potentials measured at midday for the cultivars listed in Table 1 are presented in Table 4. Although there were differences among cultivars for both leaf water potential and grain yield, there was not a strong correlation. Waldron had the lowest leaf water potential and yield among USA cultivars during both years and Cando and Vic, both durum wheats, had the highest leaf water potential and high yields.

Influence of applied fertilizer N and soil water content on leaf water potential at dawn and midday for Olaf and Alex, hard red spring wheat cultivars, is shown in Table 5 (A. B. Frank and A. Bauer, unpublished data). Nighttime recovery of leaf water potential was primarily a function of soil water treatment with applied fertilizer N having no influence. Midday depression of leaf water potential was greater in 1981 than 1982 for all N and soil water treatments. Differences in leaf water potential at dawn and midday for dryland and irrigated treatments averaged less than 0.1 MPa for both N treatments. These observations on water stress differences may be more useful in explaining yearly yield differences than in identifying drought tolerant cultivars.

PHOTOSYNTHESIS AND STOMATAL RESPONSE

Because wheat is a C_3 plant, leaf photosynthesis saturates at about 1/3 to 1/2 full sunlight. In the field, however, the photosynthetic rate of a wheat canopy may increase with photosynthetic photon flux density (PPFD) up to 2000 mol m^{-2} s^{-1} because of mutual shading in dense canopies (Baker et al., 1982; Iwaki et al., 1976; Morgan and Willis, 1983). In fact, under otherwise constant conditions, canopy photosynthesis of wheat is well described as a linear function of light intercepted by the canopy. Therefore, models such as 'Winter Wheat' are moderately successful in predicting canopy photosynthesis primarily as a function of canopy light interception (Baker et at., 1982; Morgan et al., 1983). However, a more complete response surface, including realistic effects of temperature, water status, nutrition, and shifts in source-sink relationships, must eventually be developed to permit more definitive assessments of environmental effects on photosynthesis.

Under well-illuminated conditions, photosynthetic rates of wheat canopies are sensitive to temperature (Johnson et al., 1981; Morgan and Willis, 1983). Although the determination of a single optimum temperature is made difficult because of plant preconditioning to its previous temperature regime (Berry and Bjorkman, 1980), a range of 15 to 25C appears optimum for wheat (Johnson et al., 1981; Morgan and Willis, 1983). Temperatures below 15C inhibit carboxylation reactions, but wheat canopy photosynthetic rates are only moderately affected by tempera-

Table 4. Midday leaf water potential of hard red spring and durum wheat cultivars grown at Mandan in 1980 and 1981.

	1980						
	June 9	June 17	June 23	June 30	July 3	Means	
	- - - - - - -	- - - - - - -	- MPa -	- - - - - - -	- - - - - - -		
Butte	-2.1	-2.1	-2.3	-2.7	-3.5	-2.6	
Coteau	-2.2	-2.3	-2.6	-2.8	-3.6	-2.7	
Len	-1.7	-2.0	-2.3	-2.9	-3.0	-2.4	
Lew	-2.3	-2.4	-2.3	-2.9	-3.5	-2.6	
Saratovskaya-29	-2.1	-2.8	-2.3	-3.0	-3.4	-2.7	
Waldron	-2.1	-2.4	-2.7	-3.0	-3.6	-2.8	
Cando	-1.9	-2.0	-2.4	-2.9	-3.6	-2.5	
Edmore	-1.9	-2.3	-2.6	-3.2	-3.5	-2.6	
Vic	-2.0	-2.1	-2.4	-2.6	-3.1	-2.4	
Mean	-2.0	-2.3	-2.4	-2.9	-3.2		
				1981			
	June 16	June 23	June 30	July 6	July 9	July 15	Means
Butte	-1.7	-1.6	-2.2	-2.3	-2.9	-2.4	-2.2
Coteau	-1.8	-1.7	-2.2	-2.4	-2.9	-2.2	-2.2
Len	-1.8	-1.6	-2.2	-2.5	-2.2	-2.1	-2.1
Lew	-1.6	-1.5	-2.1	-2.3	-2.5	-2.4	-2.0
Saratovskaya-29	-2.0	-1.6	-2.2	-2.4	-2.9	-2.4	-2.2
Waldron	-1.8	-1.7	-2.6	-2.6	-2.8	-2.5	-2.3
Cando	-1.6	-1.4	-2.1	-2.1	-2.6	-1.9	-1.9
Edmore	-1.5	-1.4	-2.3	-2.3	-2.9	-2.2	-2.1
Vic	-1.7	-1.6	-2.0	-2.0	-2.7	-2.3	-2.0
Means	-1.7	-1.6	-2.2	-2.3	-2.7	-2.2	

0.980, LSD (0.05) cultivars = 0.1 MPa; LSD (0.05) dates = 0.2 MPa.
0.981, LSD (0.05) cultivars = 0.1 MPa; LSD (0.05) dates = 0.1 MPa;
LSD (0.05) cultivars x dates = 0.1 MPa.

Table 5. Leaf water potential at dawn and midday for Olaf and Alex spring wheat cultivars grown at Mandan, ND under two N (0 and 118 kg/ha) and soil water levels during 1981 and 1982.

	0-N				118-N			
	Dryland		Irrigated		Dryland		Irrigated	
Variety	Dawn	Mid-day	Dawn	Mid-day	Dawn	Mid-day	Dawn	Mid-day
	- - - -	- - - -	- - - -	- MPa -	- - - -	- - - -	- - - -	- - - -
				1981†				
Olaf	-0.9	-2.1	-0.6	-1.5	-1.0	-2.0	-0.7	-1.7
Alex	-1.1	-2.1	-0.6	-1.5	-1.0	-2.1	-0.6	-1.4
				1982‡				
Olaf	-1.0	-1.5	-0.5	-1.1	-1.0	-1.9	-0.5	-1.2
Alex	-0.9	-1.7	-0.7	-1.2	-1.0	-1.9	-0.7	-1.4

†Data for 1981 are averages of four sample dates.
‡Data for 1982 are average of nine sample dates.
F-tests were significant for soil water treatment in 1981 and for water N level in 1982.

tures down to freezing (Iwaki et al., 1976; Murata and Iyama, 1963). Photorespiration rates in C_3 plants are stimulated more than are gross photosynthetic rates above 25C, resulting in marked reductions in apparent photosynthesis at elevated temperatures (Chollet and Ogren, 1975). Enzymes can become inactivated above 35C and photosynthesis ceases for practical purposes above 40C.

These temperature effects are probably not important at irradiances less than half of full sunlight when light limitations within the canopy would be overriding. An algorithm actuated at PPFD over 1000 μmol m^{-2} s^{-1} to reduce photosynthesis 35 to 50 percent for every 5° increase in temperature above the optimum and to reduce it 10 to 15 percent for every 5° temperature decrease below the optimum range (but above 5C) would improve a simple light response model. Such an algorithm would have to specify no net photosynthesis above 40C or below 0C.

Water deficits probably cause the greatest limitation on wheat yield, but plant photosynthetic responses to water stress are complex and poorly understood. These responses involve both stomatal and nonstomatal mechanisms in wheat (Frank et al., 1973; Lawlor, 1976; Morgan and Willis, 1983; Morgan, 1982, 1983). For modelling purposes, it is important to differentiate the relative importance of the two mechanisms because they do not necessarily respond to water deficits with the same overall effect on photosynthesis (Frank et al., 1973; Morgan and Willis, 1983). Little information of this kind is presently available, particularly at the plant population organizational level.

The rate and history of water stress imposition affects plant response (Morgan et al., 1983). Part of this is due to osmoconditioning, which is well documented in wheat (Morgan, J. M., 1980; Morgan, J. A., 1982, 1983). Osmoconditioning has a temporal response and has been well investigated with respect to its effects on water relations, but little of the work has dealt with photosynthetic interactions. Other aspects of plant hardening to water stress and their implication for photosynthesis are even more obscure. More work is needed in this area before simple water potential-photosynthesis algorithms can be made more realistic.

Leaf photosynthetic rate is positively associated with leaf N content in wheat (Morgan, 1982, 1983; Osman and Milthorpe, 1971). Although the major effect of increased N nutrition is thought to involve greater carboxylation capacity (Osman and Milthorpe, 1971), stomatal aperture may be indirectly influenced by increased N nutrition (Wong et al., 1979). Interactions of N nutrition and plant water status on both stomatal response and leaf photosynthesis of wheat have also been reported with N effects being most noticeable at high plant water potentials (Morgan, 1982, 1983). These data are in line with growth analysis work which shows the greatest N effects on grain yield occur with irrigation (Bauer, A., 1980). Field studies on physiological interactions of N and water on canopy photosynthesis, growth, and yield of wheat are scarce. The simple threshold type response of N nutrition on canopy photosynthesis currently used in 'Winter Wheat' with photosynthesis being affected only at tissue N concentrations of less than two percent (dry weight) (Morgan et al., 1983) is probably the most appropriate modeling technique at present.

Sink demand exerts a strong effect on

photosynthesis (Gifford and Evans, 1981). In wheat, this stimulation apparently causes higher photosynthetic rates during grain filling (Evans and Dunstone, 1970; Hodges and Kanemasu, 1977). The afternoon depression of wheat canopy photosynthetic rate in the field has been attributed to increased carbohydrates in leaves as well as to water deficits and high temperatures (Morgan and Willis, 1983). Much of the relevant data can be explained in terms of end-product inhibition, but the physiological mechanisms may not be so simple. For example, growth regulators could be involved (Gifford and Evans, 1981). Therefore, modelling with this approach should be done with caution.

SUMMARY AND CONCLUSIONS

Although progress has been made toward providing physiological insights needed to generate cereal production dynamic simulation models, much remains to be done. Yield potential in cereals is created and lost throughout the life of the crop -- from establishment of a good stand, through tillering, tiller abortion, spike development, anthesis and kernel set to the final grain filling period. Therefore, cereal yield models must have sound physiological input for all phases of the crop year.

Areas in need of research can be related to two categories: one, areas where the general pattern of plant response is already known but further development of specific information is needed, and two, relatively unexplored areas in need of in-depth study.

Although GDD will predict emergence in moist seedbeds when planting is not deep, more information is needed on effects of temperature, soil water, cultivars, and any interactions among these three factors, especially when soil water is suboptimal or when planting is deep. Furthermore, a much more complex model, requiring materials and energy flux equations, will be needed to handle such problems as soil crusting, seedbed compaction, and effects of planting machinery design on emergence. Since most present-day cultivars were selected under conventional tillage conditions, research is needed on the tillage-cultivar interactions in emergence from new types of seedbeds such as in no-till or stubble-mulch farming.

Although the general leaf and tiller developmental history of cereal crops can be traced using GDD, more evaluation is needed to incorporate day-length and radiation data into these models if appropriate. There is also need for clarification of the environmental and cultivar factors which determine the base temperature for development and which set the number of degree-days required per phyllochron. A far more complex deficiency arises from the fact that stress has not been considered in the GDD models which drive leaf and tiller development. The roles of various stresses such as leaf water deficits, low carbohydrate levels and deficient nutrient concentrations need to be clarified and threshold levels of these stresses need to be determined in the development of leaves and tillers. Fundamental research into relationships among carbohydrate sources and sinks and hormone concentrations should be done to clarify the physiology of tillering and tiller abortion.

Further work on seedlings is justified in a number of other areas. For example, the threshold temperature limits for cold damage to seedlings of spring wheats need to be determined. Drought and heat are usually studied only after the boot stage, but more information is

needed on long-term impacts of early spring water or heat stress on later development and function of the crop. For example, early stress may limit the number of seminal root axes produced. Because the earliest-produced roots have the longest time to produce deep roots, plant access to deep soil water and nutrients may be limited late in the season. The relationship between crown root depth and tiller abortion should also be determined along with effects of other stress factors.

A more quantitative approach to root extraction of soil water is also needed in these models. Such factors as plant and soil resistances to water movement need to be clarified, especially with respect to deep roots. Stomatal response to environment must be understood sufficiently well to permit models to be built with realistic algorithms for stomatal control of water loss. The role of water relations in emergence, tiller abortion, nutrient uptake, and carbohydrate production and movement needs to be clarified.

We need more precision on events early in spike development, better understanding of signals which cause the apex to become reproductive, and more information on the effects of temperature and daylength on floral conversion events for different cultivars.

Finally, the general area of management practices to reduce or control environmental and pathogenic stresses needs evaluation. Models to be used for on-farm choices of management practices must allow the costs of treatments to be compared to the expected yield increases which result from those treatments. Therefore, such models must be based on sound physiological principles and must be centered on the plant's ability to function at all stages of the crop cycle. Then models will be sufficiently realistic to be of use in crop management.

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245

CHAPTER 9. SPAR AND THE PHYSIOLOGICAL PROCESS LEVEL MODEL

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Early crop simulation research (McKinion et al., 1975) demonstrated the futility of the "standard plant" concept, i.e. attempts to extrapolate with models based on data from field plantings. This problem was addressed by the development of the soil-plant-atmosphere-research (SPAR) system (Phene, et al., 1978). A SPAR unit, diagrammed in Figure 1, is capable of the independent manipulation of individual physiological processes. The early research also demonstrated the necessity of a two-dimensional model of the rhizosphere to account for the effects of dislocations in water and nutrient supplies to the plant roots in row crops. That problem was addressed in the construction of the root-rhizosphere model, RHIZOS (Lambert, et al., 1976). Thus, the SPAR system was designed for the express purpose of process level simulation modeling.

The SPAR concept constituted a major advance beyond the conventional phytotron in several ways. The system was vastly less expensive and therefore much more easily accessible to the whole-plant modeler. Each aerial chamber receives natural solar radiation, and light attenuation by the structure is much less than in the phytotron. Plants are grown in a row crop configuration, and the units are designed with vertical shades simulating within and between row light competition. The SPAR crop is grown in a soil medium and the front wall of the soil bin was made of wire reinforced glass to permit visual observation and measurements of the root system. Later SPARs have soil temperature control. Air and soil temperature, atmospheric CO_2, and irrigation are all controlled by the computer system which provides a real time log of crop environmental variables and rates of photosynthesis, respiration and transpiration.

Thus, SPAR provides the capability to characterize the effects of various environmental factors, singly and in combination, on the various physiological process rates and organ abortion. For example, photosynthesis and photosynthate supply/demand ratios can be manipulated simply by varying the concentration of CO_2 in the SPAR atmosphere.

SPAR also provides an efficient way to evaluate model performance over its (designed) ecological range prior to field validation, i.e. a range of temperatures or soil water conditions can be provided in one experiment and rates of photosynthesis, transpiration, respiration, leaf development, tiller production, the timing of heading and the abortion of tillers or spikelets can be measured. All these data can then be compared to these events and rates predicted by the crop model. Examples of SPAR data constituting the data base in WINTER-WHEAT are presented below.

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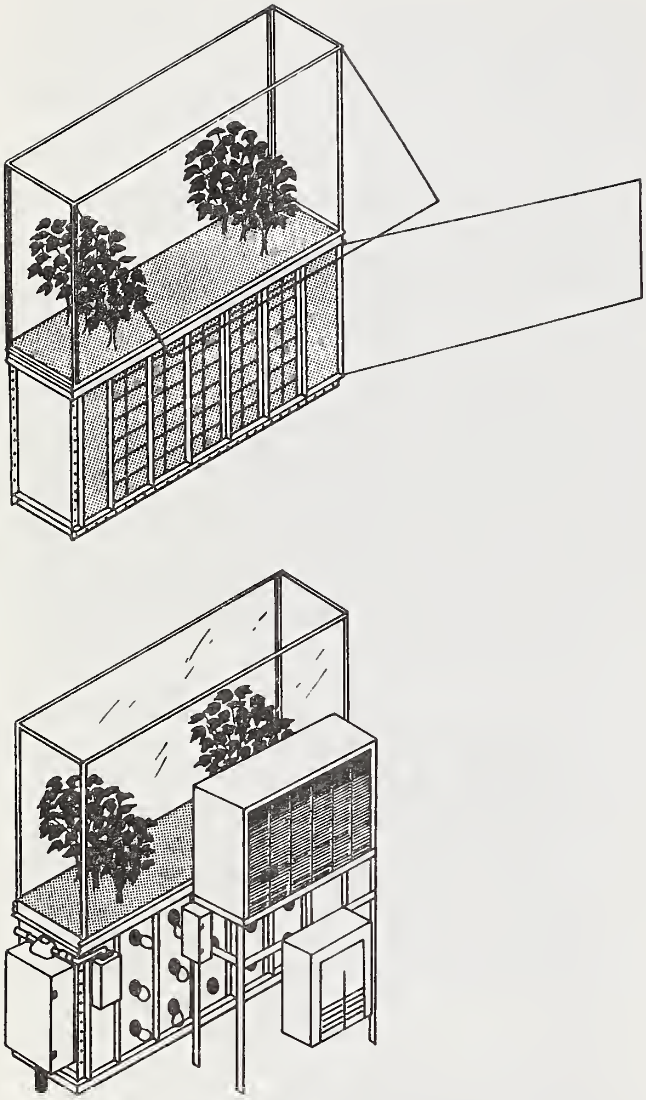

Figure 1. Front and rear views of a Soil Plant Atmosphere Research (SPAR) unit showing plexiglass top and soil bin with glass panels at front and instrument ports at back. The size of the air conditioner is exaggerated in this diagram.

PHOTOSYNTHESIS AND RESPIRATION

In 1976 at Florence, SC, three SPAR units containing Scout wheat were operated with three temperature regimes. The intermediate temperature treatment (SPAR B) represented a typical seasonal temperature pattern in the northern Great Plains. Low temperature (SPAR A) and high temperature (SPAR C) treatments were applied in the other two units; these treatments were 5°C higher and lower than the intermediate treatment (Table 1). This resulted in three different rates of plant growth, development and senescence.

An infrared gas analyzer was used to monitor and control atmospheric CO_2 in the SPARs. Each chamber was sampled once per minute. Carbon dioxide removed by photosynthesis was replaced by timed injections. The CO_2 control set-point was 320 $\mu l\ l^{-1}$. Vertical screens were maintained outside the units to simulate within and between row light competition. At several stages of development, canopy apparent photosynthesis and respiration were made via this closed system technique.

The Norfolk sandy-loam soil in the SPAR units was maintained with abundant mineral nutrients and water throughout the growing season. The soil bins were insulated but not temperature controlled. Throughout the experiment the plants appeared to be typical of healthy, vigorous crops grown in the Great Plains.

The respiration data presented in Figure 2 are typical of those obtained in this and numerous other (unpublished) SPAR experiments with wheat. Two techniques are commonly used in these measurements. In the first, the chamber is quickly darkened after a period of photosynthesis (Figure 2a). In the second, the chamber is kept dark for a period of 18 hours prior to and during the respiration measurements (Figure 2b). Rate of in-chamber atmospheric CO_2 increase is measured after 25 to

Table 1. SPAR Unit Temperature Control Program for 1976.

Day of Year	Average SPAR Air Temperature °C SPAR UNIT A	B	C
6-12	2.7	5.3	9.8
13-19	4.6	7.2	10.1
20-26	4.9	7.1	12.8
27-33	4.6	9.7	12.8
34-40	7.2	10.2	15.6
41-47	7.2	12.8	18.3
48-54	7.2	12.8	18.3
55-61	10.0	15.5	21.1
62-68	10.0	15.6	23.9
69-75	10.1	18.0	23.5
76-82	12.6	18.0	23.6
83-89	13.1	18.3	25.8
90-96	15.9	21.2	29.3
97-103	16.0	23.9	29.4
104-110	18.2	23.9	29.3
111-117	18.2	23.8	28.8
118-124	17.9	24.1	29.3
125-131	19.0	23.8	28.7
132-138	18.0	23.0	27.4*
139-145	16.8	23.8	
146-152	17.2	23.9	
153-159	17.1	23.8	

*Terminated after day 137

30 minutes' of plant adjustment to a new temperature level.

Unlike the results with cotton (Baker et al., 1972), in wheat we have found no difference in rate of canopy respiration whether preceded by a period of rapid photosynthesis or not. The crop grown at high temperatures (SPAR C) was well into senescence when these measurements were made. Therefore, those data points were deleted in the analysis of the data. The relationships between respiration rate and temperature were not significantly different after periods of rapid photosynthesis, or after a long exposure to darkness. Therefore the light and dark respiration data were pooled and fitted to a single curve for use in the simulation model.

The technique for "light" respiration measurement may be criticized because it is, in fact, a respiration measurement made in the dark and used to represent respiration in the light (Chollet and Ogren, 1975). Although we believe any quantitative error will be relatively small, this estimate of the respiratory loss in the light will probably be on the high side. Canvin (1970) presents evidence that dark respiration may be reduced in the presence of light.

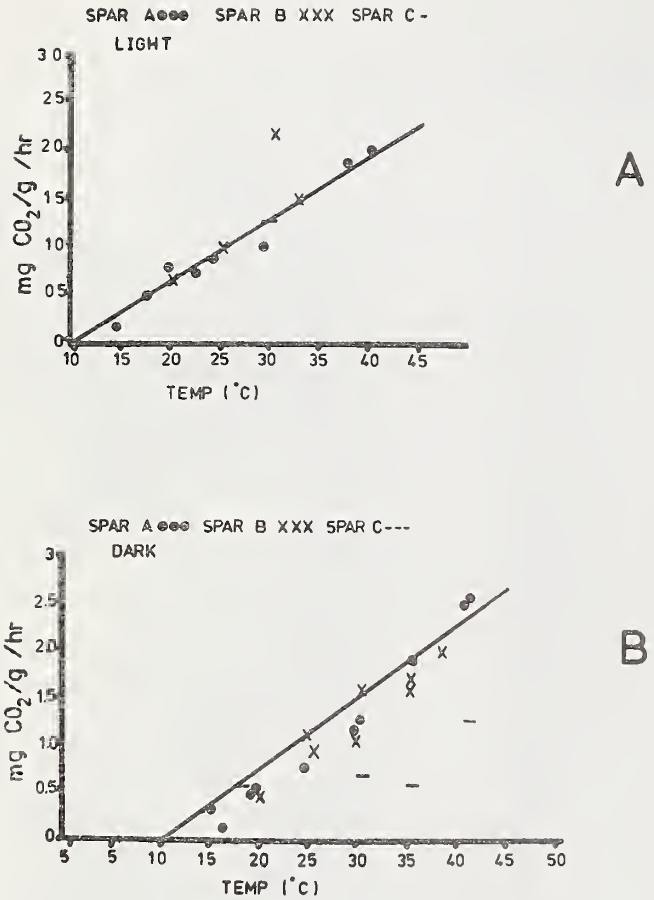

Figure 2. Canopy respiration rates (in mg. CO_2/gram dry plant weight/hour) vs. air temperature immediately after exposure to bright light (A) and after exposure to long periods of darkness (B).

There appeared to be no change in canopy photosynthetic efficiency during the season until the beginning of senescence. The effect of canopy senescence can be seen in the light response curves in Figure 3. There was no significant senescence in SPAR A noticeable through days 126, 127, and 128.

Appropriate dark respiration values from the above measurements were added

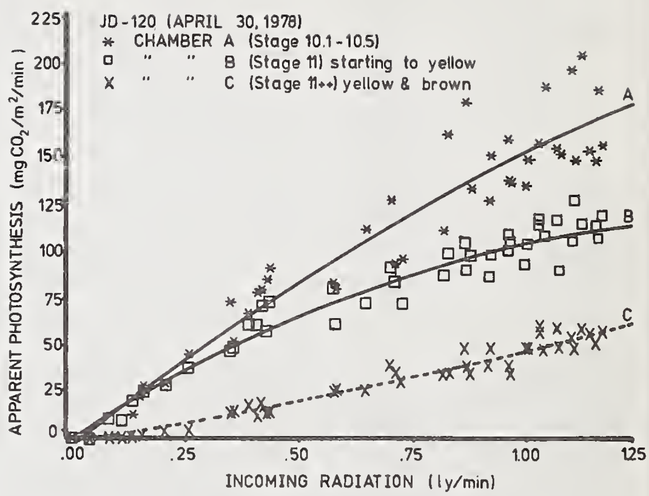

Figure 3. Apparent canopy photosynthesis vs. solar radiation flux density in three SPAR crops differing in maturity.

to these (15-minute) apparent photosynthesis values, and, the data were pooled to obtain a composite canopy light response curve (quadratic) with 258 15-minute data points. An R^2 value of 0.89 was obtained. This curve was used, with 15-minute average incoming solar radiation data throughout the daylight periods in 36 representative days over the season to produce the daily total data presented in Figure 4. The data range from completely clear days to completely and heavily overcast days. In the first draft of the PNET subroutine of the WINTER WHEAT model, leaf area was used to calculate canopy light interception and this equation was used to calculate daily photosynthate production from daily total solar radiation. Subsequent SPAR experiments in which soil nitrogen and water supplies were varied have provided empirical reduction factors both for direct effects on photosynthesis and respiration and the indirect effects due to stress induced changes in senescence rates.

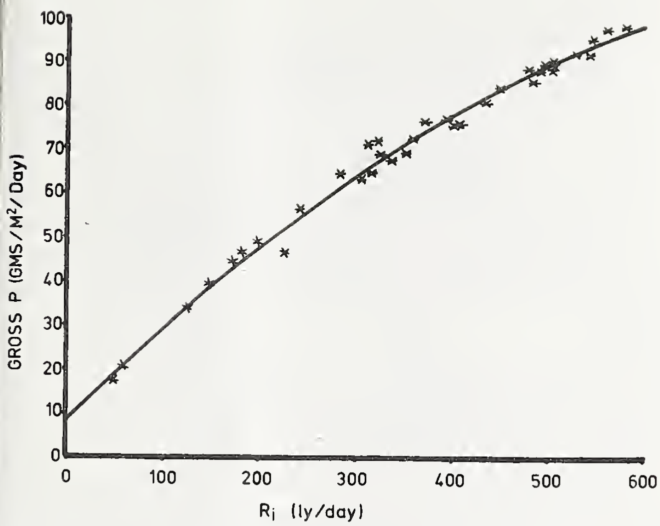

Figure 4. Daily total canopy photosynthesis vs. daily total solar radiation.

GROWTH

As noted elsewhere (Baker, et al., 1985), modeling strategy dictates that "genetic potential" rates of plant growth and development are characterized in the initial SPAR experiments. After the "genetic potential" growth and development rates are defined, other SPAR experiments characterize the effects of various stresses in reducing plant growth and development. Stress is defined as any factor which limits organ expansion, and this may include a carbohydrate source: sink imbalance. In SPAR experiments, sink strength is manipulated by varying plant turgor, temperature, and mineral nutrients. Carbohydrate supplies are manipulated by varying atmospheric CO_2 concentration and photosynthesis.

SPAR data files on the rates of wheat organ growth and plant development under nonstress conditions are now extensive, although few have been published. Typical data for leaf area and head growth (from Eissa, et al., 1983) are presented in Figures 5 and 6. Four SPAR units containing winter wheat (cv. Scout) were maintained at 600 $\mu l\ l^{-1}$ atmospheric CO_2, and supplied with abundant soil water and mineral nutrients. Temperature programs similar to those illustrated in Table 1 were maintained. The final air temperatures are included on the figures to indicate the temperature treatments. The time courses of head dry matter and leaf area accumulation are graphed against heat sums computed from a 0°C base.

Figure 5 shows that prior to 500 heat units leaf area growth was exponential. At that time LAI's were about 4, there 18 tillers per plant, and tillering was continuing. Due to the large numbers of tillers and leaves, the succeeding linear growth period probably represents a photosynthate limiting situation with growth rate of the total leaf canopy proportional to photosynthate supply. Weather source limited, due to the large number of growing tillers and leaves, or not, the rate depicted here should represent a useful maximum.

At the end of the vegetative growth period the plants were thinned to 3 to 5 tillers/plant. Average head dry weights are graphed against calendar date in Figure 6. The initial slopes are similar regardless of temperature, and the slopes during the grand period of grain growth are similar. However, temperature had a major effect on grain yield through its effect on the length of the grain filling period. Thus, the primary effect of temperature during this growth stage was on rate of developmental events, i.e. senescence.

DEVELOPMENT

The phenology of the wheat plant is

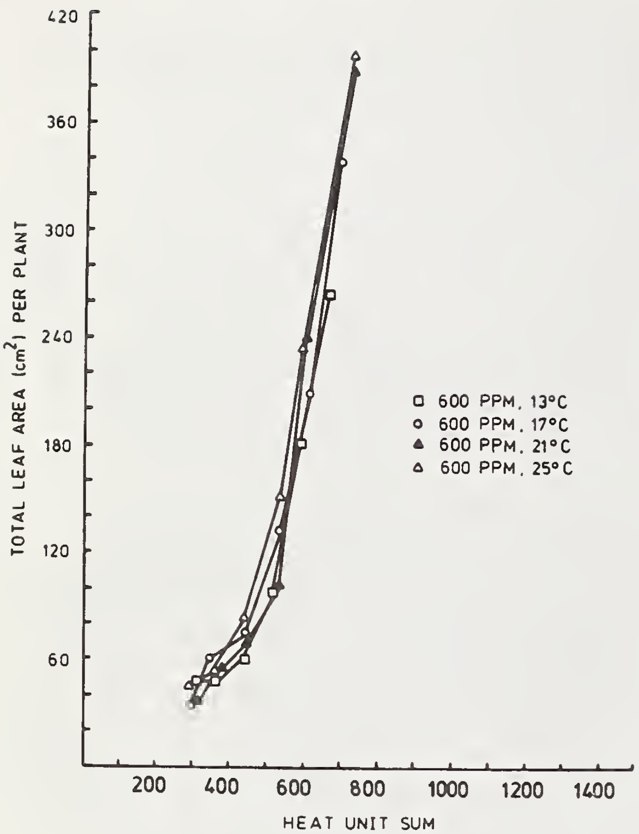

Figure 5. Total leaf area per plant vs. heat units summed above 0°C..

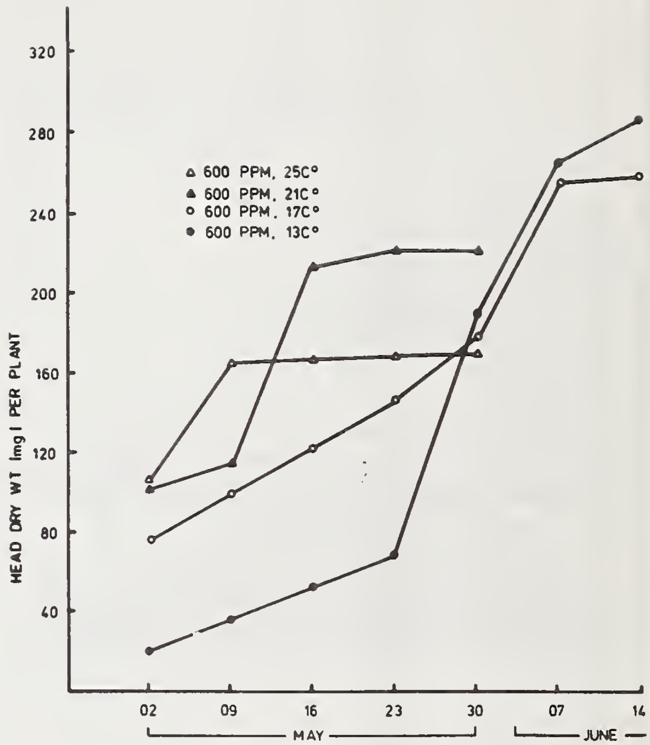

Figure 6. Time courses of head dry weight accumulation at four temperatures.

simulated by estimating the effect of environmental factors on plant developmental rates. As is the case with growth, development records are obtained in SPAR experiments where temperature is controlled and varied systematically in order to characterize the system over the ecological range of interest.

An example of SPAR data describing developmental rates is presented in Figure 7. They are from the 1976 experiment in a 320 µl 1^{-1} CO_2 atmosphere. The temperature treatments are presented in Table 1. For use in the simulation model, the stages recorded in Figure 7 and the temperature data in Table 1 are summarized to express

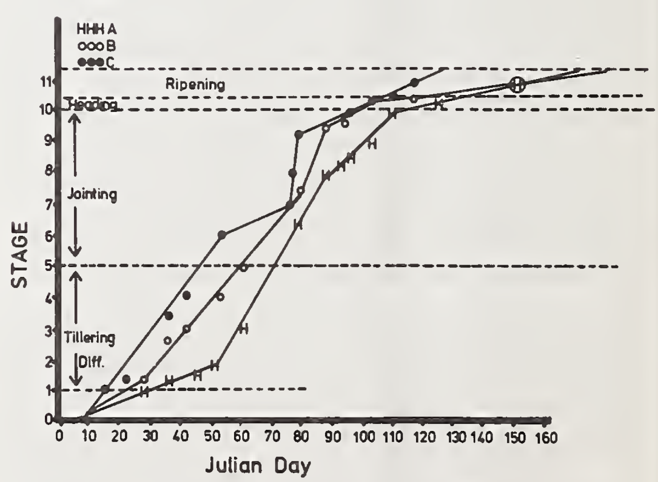

Figure 7. Developmental stage vs. day-of-year (Julian) date for wheat crops maintained in three different temperature regimes.

stage-to-stage developmental transition either as functions of heat unit accumulation from one stage to the next, or as functions of running average temperatures for the periods between stages. Some developmental events may be delayed by physiological stress. Therefore, the rate equations used in the model contain stress terms developed from other SPAR experiments in which various stresses are systematically applied.

Phenological events are only part of the developmental information needed in crop simulation. The initiation, senescence, and abortion of tillers, leaves, and florets must also be recorded in controlled environment experiments.

SUMMARY

The soil-plant-atmosphere-research (SPAR) system was developed as a result of failures in attempts to use models based on field observations of plant responses. Thus, SPAR was designed expressly for the purpose of physiological process level crop simulation modeling. It represented a major advance beyond the classical phytotron in terms of cost and because light and root zone conditions much more closely resembled those in the field. The physiological processes controlled and measured in SPAR experiments in connection with the development of WINTER-WHEAT include photosynthesis, respiration, transpiration, organ growth (including roots) and development. SPAR provides the capability to manipulate stress systematically, permitting the development of models which simulate stress induced senescence and organ abortion.

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245

CHAPTER 10. DESCRIPTION AND PERFORMANCE OF CERES-WHEAT: A USER-ORIENTED WHEAT YIELD MODEL

J. T. Ritchie and S. Otter[1]

INTRODUCTION

CERES-Wheat is a wheat yield model developed as a result of the ARS-Wheat Yield Project and the U. S. Government Multi-Agency AgRISTARS program. It was developed to meet the need of user agencies having primary responsibilities for making large-area yield forecasts for the U. S. and abroad. At the beginning of the ARS-Wheat Project, representatives from these agencies indicated that their present techniques, consisting mostly of statistical models, had several weaknesses that limited their reliability. They were requesting the assistance of a research group like ARS for ideas on modifying their present procedures or for developing entirely new modeling approaches to the problem.

Our early interests at Temple were modeling the soil water balance and how water deficits influence crop growth and yield. We had experienced limited success in modeling the water balance in a general way so that the model could be used successfully anywhere in the world. The problem with using the model, however, had been that the important input information on leaf area index (LAI) over the season was often not available. Our ARS group, in cooperation with Texas A&M scientists, then attempted to model the LAI of grain sorghum as a means of approximating LAI values needed in the water balance model. We demonstrated fairly good generality in a grain sorghum model, at least for the U. S. Great Plains area (Arkin et al., 1976). That model could also estimate biomass reasonably well using a simple light interception model.

From the success in modeling the soil water balance and grain sorghum LAI and biomass, it seemed only reasonable to use similar principles to develop a wheat yield model. The challenge, however, was to add genetic characteristics to the modeling concepts for global applicability and to develop relatively simple assimilate partitioning procedures so that yield components could be estimated. With the assistance primarily of H. A. Nix, R. A. Fischer, J. N. Gallagher, and H. J. Spiertz from outside the U. S., and several Federal and State scientists in the U. S., some procedures for incorporating genetic and partitioning factors into a model were developed. These procedures became the basis for parts of the CERES-Wheat Model.

The word CERES is a Greek word from which we have obtained the word cereal. It is an acronym for Crop Estimation through Resource and Environment Synthesis. The major purpose of the CERES models developed by the ARS Crop Systems Evaluation Research Unit at Temple is to provide users with an operational model that could be used for the following applications:

- --- Assistance with farm decision making
- --- Risk analysis for strategic planning
- --- Within-year management decisions
- --- Large area yield forecasting; foreign and domestic
- --- Policy analysis
- --- Definition of research needs

In order to achieve these objectives, it was necessary to become familiar

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with procedures presently being used for some of the various purposes listed above and to understand some of the limitations encountered in making a model useful for a specific purpose. The main features needed for a user-oriented model appeared to be: (1) The input information on weather, soils, and genetics should be available, (2) it should be written in a familiar computer language, and (3) the computational time should be minimal. Most of the input information needed for CERES is available from routinely collected daily weather data and soil information from standard soil classification data. The program is written in a familiar programming language, FORTRAN, and runs on a main-frame computer such as the AMDHAL 470. Simulation of a growing season uses about one second of central processing unit time.

In order to simplify the model as much as possible, many "rational empiricisms" are used to indirectly incorporate information from several levels of organization into relationships needed to make the model work for a community of plants growing in a field environment. Sometimes the empiricisms can be obtained from simplications of more complex models of certain processes. To be sufficiently general, the model must incorporate information from at least 8 levels of biological organization. These levels include molecules, cell structures, cells, tissue, organs, individuals, populations, and communities. Including all these levels of organization into a model system would be practically impossible. For example, the yield model has to directly or indirectly evaluate the uptake of CO_2 molecules through stomata on leaves of individual crop plants growing in a community of plants competing for resources over all or part of a year. To completely simulate these processes according to known principles available from each level of organization would require massive computer time and programming and almost minute-by-minute values of radiation and temperature. However, Monteith (1977) has demonstrated that a quite general empiricism to calculate biomass production for plant communities can be obtained by using total daily radiation interception, with modification for extremes in temperature or for water stress. We have found other useful empiricisms to describe the main features of other important processes that vary considerably in short-time intervals such as leaf extension growth, transpiration, infiltration, and drainage.

MAIN FEATURES OF CERES-WHEAT

Because the purpose of CERES-Wheat is to provide yield estimation to users, the main features of the model deal with the factors considered to be most influential in determining final yields. These include:

- --- Phasic development or duration of growth stages as related to plant genetics, weather, and other environmental factors
- --- Apical development as related to morphogenesis of vegetative and reproductive structures
- --- Extension growth of leaves and stems and senescence of leaves
- --- Biomass accumulation and partitioning
- --- Soil water deficit impact on growth and development
- --- Nitrogen deficit impact on growth and development

Obviously, there are many factors overlooked in the list that cause reductions in crop yields. Such limiting factors include weeds, diseases, and insects. This type of problem is not included in the general models because

the factors are more random in nature, they can usually be controlled through management, and the species are so numerous and varied that they could not be dealt with in balance with other components of the model. However, leaving out these and other known important limiting factors on yield in the general model by no means minimizes their importance nor does it imply that they are too complex to model. A particular limiting factor could be added to the general crop model for a specific application.

Although it would be desirable to discuss the scientific principles in the empirical relationships used in CERES-Wheat, this paper provides only a general description of the model. More detail is available in the preliminary model documentation (Ritchie and Otter, 1984). Also, because the nitrogen dynamics section of the model was mainly developed for management-related problems rather than large-area yield estimation, it will not be discussed here.

Inputs needed for CERES-Wheat are related to weather, soil, genetics and management. Weather inputs are restricted to daily solar radiation, maximum and minimum air temperature, and precipitation. These values are usually available at many locations with the exception of solar radiation. Solar radiation can be approximated from percent of possible sunshine data. In the future, solar radiation will likely be available in mapped form from NOAA-National Environmental Satellite Service for all the 48 contiguous states. There is presently an operational test of the solar radiation estimating program.

Soil input information needed includes drainage and runoff coefficients, evaporation and radiation reflection coefficients, soil water-holding capacity amounts, and rooting preference coefficients at several depth increments. It also requires saturated soil water content and initial soil water content for the first day of the weather data series.

Genetic input information needed are coefficients related to photoperiod sensitivity, duration of grain filling, conversion of mass to grain number, grain filling rates, vernalization requirements, stem size, and cold hardiness.

Management input information required is plant population, planting depth, and date of planting. If irrigation is used, the date of application and amount is required. Latitude of site is another needed input. The model can use different weather, soils, genetic and management information within a growing season or for different seasons in a single model execution. A few input parameters are used to control the input information for each growing season.

PHASIC DEVELOPMENT

Phasic development in CERES-Wheat deals with the duration of growth stages. The growth stages are organized around times in the plant life cycle when changes occur in partitioning of assimilate among different plant organs. For example, prior to terminal spikelet formation, all assimilate is partitioned between leaves and roots. After terminal spikelet formation, stems begin to require assimilate and later the ear becomes a major site for assimilates.

The growth stages are numbered between 1 and 9. Stages 1 through 5 are the active above-ground growing stages and

the remainder are used to describe other important events in the crop cycle. The growth stages include:

Stage No.	Event	Plant Parts Growing
7	Fallow or presowing	
8	Sowing to germination	
9	Germination to emergence	roots, coleoptile
1	Emergence to terminal spikelet initiation	roots, leaves
2	Terminal spikelet to end of leaf growth	roots, leaves, stems
3	End of leaf growth to end of pre-anthesis ear growth	roots, stems, ear
4	End of pre-anthesis ear growth to beginning of grain filling	roots, stems
5	Grain filling	roots, stems, grain
6	End of grain filling to harvest	

Phasic Development Control

Both genotype and environment influence the phasic development in CERES-Wheat. The primary variable influencing development rate is temperature. We assumed that development rates are directly proportional to temperature in the range from the base temperature of 0°C to a maximum temperature of about 30°C. Thus we accumulate daily temperature above 0°C and refer to that as thermal time.

When the minimum temperature is above 0°C and the maximum is below 30°C, thermal time for a day is assumed to be the mean of the two values. If either the maximum or minimum temperature is out of that range, a separate thermal time calculation is made using the mean temperature and temperature range.

The thermal time for all growth stages is not fixed. Vernalization, photoperiod, and genetic characteristics cause total thermal time for stage 1 to vary considerably. Thermal time for stage 5 (grain fill) is variable between genotypes. In other stages, plants have fixed thermal time duration except for sowing to germination. That process is assumed to take one day where there is adequate soil water in the seed zone. Germination is delayed if the soil water is below a threshold value, or if the mean temperature is below 3°C.

Winter wheats require exposure to relatively low temperatures before spikelet formation can normally occur. The phenomenon is called vernalization. Vernalization begins at germination. Synthesis of literature and some of our own phytotron work suggests that vernalization does not occur below 0°C nor above 15°C. Optimum temperature for vernalization is assumed to be in the 0°C to 7°C range with a decreasing influence between 7°C and 15°C. Maximum and minimum temperatures are used to calculate a daily vernalization effectiveness factor between 0 and 1. The effectiveness factor is then accumulated to determine duration of effective vernalization or vernalization days. Fifty vernalization days are considered sufficient for all cultivars, but there is genetic variability in sensitivity to vernalization. Thus we use a genetic specific coefficient (PIV) to calculate the influence of vernalization on the duration of growth

stage 1. Spring wheats have a low sensitivity to vernalization. This is considered in the model through the vernalization coefficient (P1V).

In some instances devernalization can occur when young seedlings are exposed to high temperatures. In the model, if the vernalization-days are below 10 and the maximum temperature exceeds 30°C, then vernalization days decrease in proportion to the temperature above 30°C.

Photoperiod also can cause a delay in plant development in stage 1. In CERES-Wheat, daylengths shorter than 20 hours cause a delay in development somewhat proportional to the shortness of the day. The extent of the delay is dependent on a genetic-specific characteristic (P1D). Photoperiods calculated in the model include civil twilight.

Vernalization days and photoperiod are used to modify the accumulation of thermal time in stage 1. Vernalization and photoperiod factors with values between 0 and 1 are calculated using the P1V and P1D coefficients and the minimum value of the two is multiplied by the thermal time to reduce the usual thermal time calculations. When the reduced thermal time reaches 400 degree days, stage 1 ends. We believe this procedure for determining when terminal spikelet occurs can be improved, but more research will be required.

GROWTH AND ORGAN DEVELOPMENT

Dry Matter Production

In CERES-Wheat, potential dry matter production is a linear function of intercepted photosynthetically active radiation (PAR). The constant for conversion is 3.05 grams biomass per MJ of intercepted PAR. The value of PAR above the canopy is equal to 50% of the incoming solar radiation after conversion of the units from langleys to MJ per square meter. The percentage of incoming PAR intercepted by the canopy is an exponential function of leaf area index (LAI).

The actual rate of dry matter production is usually less than the potential rate due to the effects of non-optimal temperature or water stress. A weighted daytime temperature is calculated from the minimum and maximum temperatures for use in the biomass evaluation. The optimum daytime temperature is considered as 18 C. Water stress reduces dry matter production rates below the potential whenever crop extraction of soil water falls below the potential transpiration rate calculated for the crop.

Leaf and Tiller Development and Expansion Growth

Plant leaf area has an important influence on light interception and dry matter production. The rate of leaf area expansion is a component of plant growth that is quite sensitive to environmental stresses. For example, leaf growth is more sensitive to plant water deficits than photosynthesis. In addition, the optimum temperature for leaf growth is several degrees higher than for photosynthesis. Thus, cool temperatures or moderate drought stresses reduce expansion growth more than photosynthesis is reduced, causing increases in specific leaf weight and increasing the proportion of assimilate partitioned to roots. CERES-Wheat accounts for these plant responses by using separate relationships to calculate the influence of temperature and water deficits on photosynthesis and leaf growth.

The daily growth of plant leaf area is the product of the total width of expanding leaves on a plant, the maximum daily rate of length extension growth of a leaf, a reduction factor for non-optimal temperatures, and a reduction factor for water deficit. Total width of expanding leaves is the product of the number of growing leaves on a plant including tillers and the average width of a leaf. An empirical expression is used to combine leaf appearance rates with tillering rates to determine average number of growing leaves and their width. The optimum temperature for leaf expansion growth is 21°C. Soil water availability can limit leaf growth even before transpiration is reduced. Whenever maximum possible root water absorption on a day is less than 1.5 times the potential transpiration, the rate of leaf extension decreases. This important part of the model, especially for stage 1 growth, can likely be improved, but data sets available often lack details necessary to evaluate or improve the model.

Leaf Senescence

Leaf senescence is primarily coupled with crop phasic development. Senescence is initially slow, increasing as the plant approaches physiological maturity. In addition to natural senescence with normal phasic development, low temperatures and water deficits can accelerate senescence. Competition for light in dense canopies also hastens senescence. For cold temperature stresses, the degree of senescence is affected by the degree to which the crop has hardened from previous exposure to cold temperatures. Unhardened leaves are more susceptible to rapid leaf senescence than hardened leaves.

Tiller Death

Usually there are several more tillers developed and visible at terminal spikelet formation than can become full mature tillers with heads. Accounting for this loss of tiller growth has been one of the more difficult parts of wheat growth modeling. Thus it is common to make sizable errors in the final tiller numbers with the model when comparing the output with measured field data. However, this factor does not cause a serious error in the grain number or yield calculations because the number of tillers expanding stems is controlled by a source-sink balance. Thus, if tiller number estimation is low, tiller size is high and vice-versa. Tiller loss occurs in stage 2 when the stems are actively expanding. In the model, the potential growth rate of a single stem is calculated, based on a genetic-specific characteristic which distinguishes between wheat stem growth habits. The biomass allocated to stem growth of an entire plant on a given day is divided by the biomass required per individual stem to determine how many stems can expand with the available assimilate supply. A time lag factor prevents rapid decreases in tiller number due to large day to day variations in photosynthesis rates.

Root Growth

Biomass is partitioned into shoots and roots. The proportion partitioned to roots affects root density and thus the ability of the root system to supply the shoot with water and nutrients. The fraction of dry matter production partitioned to the root depends primarily on the growth stage of the crop. The fraction partitioned to roots usu-

ally declines as the plant matures. However, at all growth stages except stage 5, the fraction partitioned to roots increases with water deficits. When competition for light is high with dense canopies, the fraction partitioned to roots decreases. These compensating mechanisms are certainly real but have been difficult to quantitatively describe in the model.

The total growth of roots in a day is determined by the amount of biomass partitioned to the roots. To determine the distribution of roots in the soil, a rooting preference factor is input for each soil layer. The preference factor usually decreases rapidly with depth but root restricting factors may vary at any soil depth. The preference factor of a layer is reduced when the soil water content is below a threshold value. Thus, when a particular soil layer becomes quite dry, root growth in that layer decreases, but compensatory root growth normally occurs elsewhere in the profile where the water status is more favorable.

Grain Number and Kernel Growth Rates

In CERES-Wheat the number of grains per plant is a linear function of a genetic factor and stem plus ear weight at the end of growth stage 4. The assumption is that if conditions during stem and pre-anthesis ear growth favor large stems and ears, then grain numbers will be high. The genetic coefficient accounts for known differences between genotypes in number of grains per ear. If severe stresses occur during grain filling, some grain abortion will occur to reduce final grain numbers.

The maximum possible kernel growth rate during stage 5 is an input genetic parameter. Kernel growth rate can be reduced from the maximum when mean temperatures drop below about 17°C or when the total kernel sink demand for assimilate exceeds the available supply. The assimilate supply comes from both current assimilate and stored assimilate. The supply of stored assimilate is assumed to be equal to the amount of assimilate partitioned to the stem during stage 4 plus excess assimilate not needed for grain filling during stage 5. Plant water deficits have no effect on grain filling except indirectly through a reduction in the assimilate supply during grain filling.

Final grain yield is the product of plant population, kernels per plant and weight per kernel.

SOIL WATER BALANCE

The soil water balance is calculated in CERES-Wheat in order to evaluate the possible yield reduction caused by soil and plant water deficits. As a model option controlled by an input parameter, the soil water balance can be assumed non-limiting for all plant processes in the model. In that case, the water balance routine is by-passed.

The soil inputs set several user-selected soil depth increments where water balance calculations are made. Water contents in any layer can increase due to infiltration of rain, melted snow, irrigation water, or due to flow from an adjacent layer. Water content can decrease due to soil evaporation, root absorption or flow to an adjacent layer. The limits to which water content increase or decrease are also input for each layer as the lower limit of plant water availability, the field drained upper limit and the field saturated water content. These input limits are quite important in model runs where water availability is marginal and the traditional techniques

for estimating them may not be accurate enough. Our research unit has reported on this problem and suggested possible solutions for obtaining improved input limits in 3 papers; Ritchie (1981), Ratliff, Ritchie and Cassel (1983), and Cassel, Ratliff and Ritchie (1983).

Infiltration is calculated as the difference between daily precipitation or snowfall and runoff. Runoff is estimated using a Soil Conservation Service Curve Number technique as modified for layered soil by J. R. Williams (personal communication) in other hydrology models. When irrigation inputs are encountered in the model, the runoff estimation is by-passed in order to allow all irrigation to infiltrate.

Because of the need to estimate snow depth for the cold hardening and winter killing part of CERES, an empirical approach is used to estimate snow depth. Snow accumulates when the daily maximum temperature is less than 1°C. We assume 1 cm of snow per mm rain under those conditions. Snow melts at a rate proportional to the daily maximum temperature and the rainfall amount.

Drainage is calculated as a function of the water content above the drained upper limit (DUL). A single drainage coefficient for the entire profile is input from the soils information that varies between 0 and 1. The constant is used for drainage from every soil layer under the assumption that a most limiting layer for water flow will dominate the drainage from the entire profile. The drainage coefficient represents the fraction of the water content between the DUL and field saturation that can drain in successive days after the soil is wet to saturation. Thus, if the coefficient is 0.5, half the water between DUL and saturation will drain the first day, half the remaining will drain the second day and half the remaining the third day, etc. For this example 87.5% of the difference between the DUL and saturation will have drained in three days. Drainage from the entire profile is represented by the drainage calculated from the lowest soil layer.

Evapotranspiration (ET) is calculated using procedures as primarily presented in a published model (Ritchie, 1972). The procedure separates soil evaporation (ES) from transpiration (EP) for plants growing without a shortage of soil water, primarily on the basis of energy reaching the soil, the time after the surface layer is wet and the LAI. Potential ET is calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972). A relatively simple empirical equation was developed from several rather complex exponential equations needed to evaluate the net radiation and temperature influence on equilibrium evaporation. The equation approximates the daytime net radiation and equilibrium evaporation, assuming that stomata are closed at night and no ET occurs. The potential ET is calculated as the equilibrium evaporation times a constant (1.1) to account for unsaturated air. The constant is increased above 1.1 to account for advection when the maximum temperature is greater than 24°C. The constant is reduced for temperatures below 0°C to account for cold temperature influence on stomata closing.

The drying stage ES in the Ritchie (1972) model was altered for CERES-Wheat to further reduce ES when the soil water content in the upper soil layer reaches a low threshold value. This modification is needed for layered soils water balance evaluations to prevent the surface soil from drying

too much when root water absorption is also removing water from near the surface.

Root water uptake is calculated using an empirical evaluation of the maximum possible single root water uptake rates. The radial resistance to water flow into roots is assumed to vary with flow rates in such a way that any flow rate per unit root length can be accommodated up to a certain limiting maximum value. This maximum uptake per unit length as limited by soil water flow is calculated from a generalized hydraulic conductivity relation for each soil depth with a slight variation in the relation resulting from different root length densities. The maximum possible water uptake rate is assumed to be equal to the minimum value of the soil-limited or root-limited uptake rate.

Using estimates of root length density calculated from the root growth section of the model and soil water estimates, the maximum possible uptake per unit root length in each soil layer is then converted to the maximum uptake for the entire root system. If this maximum uptake value exceeds the calculated potential transpiration, then transpiration is assumed to occur at the potential rate. Under those circumstances, the calculated maximum uptake from each soil layer is reduced to the actual uptake by multiplying by the radio of transpiration to maximum total profile uptake. This procedure makes the total soil water uptake equal to the potential transpiration. If the maximum uptake for the entire root zone is less than potential transpiration, then the actual uptake becomes the maximum uptake, and the transpiration is reduced to that value. This reduction in transpiration, expressed as a fraction of the potential, is also used to reduce photosynthesis in the growth subroutine. When the ratio of maximum uptake to transpiration falls below 1.5, leaf and stem extension growth start to be reduced.

The potential rate of downward root growth is assumed to be proportional to the rate of plant development, and thus is controlled by temperature. The potential rate is reduced if the whole plant root absorption is less than the potential transpiration or if the soil layer where the front of new downward growth is occurring is below a threshold water content. The input root preference factor for each soil depth is used with the depth of rooting and the water content of each depth to determine the distribution of root growth in the profile. The mass of assimilate partitioned to the roots, as calculated in the plant growth section of the model, is converted to a root length, assuming a constant proportionality between root mass and length, to provide estimates of root length density. There is a small reduction in root length in each depth to account for root sloughing.

COLD HARDENING AND WINTER KILL

Under certain conditions, wheat plants can be killed or severely damaged by extremely low temperatures. The extent of the damage often is related to the hardening that has occurred prior to the low temperature event and the amount of protection the plants receive from snow cover. CERES-Wheat attempts to account for this possible loss because of its importance in large regions where wheat is grown.

The estimated crown-depth temperature is used to evaluate cold hardening and killing. Crown depth temperatures are calculated from empirical relations developed from data reported by Aase

and Siddoway (1979). They found that crown depth soil temperature was proportional to air temperatures below 0°C, with the proportionality being dependent on snow depth.

Hardening is assumed to occur in two phases. In the first phase, hardening occurs when the soil mean crown temperature is between -1°C and 8°C. Ten days in this temperature range completes stage 1 hardening. Stage 2 hardening occurs after stage 1 hardening is complete and when the temperatures are below 0°C. Twelve days of this condition complete stage 2 hardening, resulting in a fully hardened plant.

The point at which tillers begin to be killed by low temperatures is a function of a hardening index that varies between 0 and 1 for stage 1 hardening and between 1 and 2 for stage 2 hardening. The threshold killing crown temperature is -6°C, -12°C and -18°C for hardening index values of 0, 1 and 2, respectively. Tiller numbers are reduced in proportion to the degree of coldness below the threshold killing temperature. If all tillers except the main stem are killed, the plant population is reduced in a similar way to the tiller loss.

Dehardening occurs when the crown temperature is 8°C. Under this condition, snow depth is assumed to be zero and the maximum temperature is used to calculate dehardening. The dehardening rate is proportional to the maximum temperature when it is above 10°C. The dehardening rate is twice as fast in stage 2 hardening than it is in stage 1 hardening. Many of the principles for the hardening and dehardening concepts used in CERES-Wheat were obtained from work of Gusta and Fowler (1976).

OUTPUT OPTIONS FOR USERS

Three types of output are available when using CERES-Wheat. A summary output is always printed. This output includes the identification of the run assigned by the user and most of the other input information on genetics, soils and management. When the development stage changes from one phase to another, the summary lists the calendar date, the day of the year, the cumulative thermal time after sowing, the above-ground biomass, and LAI. Yield and yield components are output at the end of stage 5. The summary output sheet also includes at each phase change an average of the stress coefficients for photosynthesis and extension growth during each phase of development and along with growing season cumulative values of ET, ES, EP (transpiration), and precipitation. Total potentially extractable soil water in the whole profile is also listed for each phase change. All these summary output details provide the user with information on the response of the crop for more detailed evaluation of yield response. An example summary output is shown in Figure 1.

Two optional output records are available to give greater details about the water balance components and growth components calculated with the model. For these optional output records, the frequency of output can be specified.

For the water balance, run information listed includes date of output, soil water content in each layer along with the total extractable water on that date, average daily ES, EP, ET and potential ET, solar radiation, and maximum and minimum temperatures for the period the user specifies is also

WEATHER=BUSHL077 BUSHLAND - TEXAS 1977 - 1978 PD-2 T-4

VARIETY NUMBER 541 VARIETY NAME TAM W 101

LATITUDE = 35.2 , SOWING DEPTH = 11. CM , PLANT POPULATION = 230.PLANTS PER SQ METER

GENETIC SPECIFIC CONSTANTS P1V =0.018 P1D =0.0060 P5= 480. G2 = 17.00 G3 = 1.38 G4 = 0.63

SOIL ALBEDO= 0.12 U= 6.0 SWCON= 0.50 RUNOFF CURVE NO.= 60.0 SOIL NO.= 3

JULIAN DAY	IRRIGATION(MM)
286	100.
341	100.
82	100.
98	100.
115	100.
138	100.

DEPTH-CM	LOW LIM	UP LIM	SAT SW	EXT SW	INIT SW	WR
0.- 15.	0.180	0.323	0.383	0.143	0.260	1.000
15.- 30.	0.220	0.357	0.383	0.137	0.280	0.700
30.- 60.	0.215	0.329	0.362	0.114	0.230	0.300
60.- 90.	0.170	0.288	0.335	0.118	0.170	0.100
90.- 120.	0.170	0.261	0.311	0.091	0.190	0.050
120.- 150.	0.170	0.260	0.290	0.090	0.200	0.025
150.- 180.	0.170	0.260	0.290	0.090	0.220	0.012
180.- 210.	0.170	0.260	0.290	0.090	0.240	0.005
210.0	37.9	59.9	67.8	22.0	45.6	TOTAL FOR PROFILE

THE PROGRAM STARTED ON JULIAN DAY 210

DATE	JUL DAY	CUM DTT	PHENOLOGICAL STAGE	BIOMASS	LAI	CSD1	CSD2	WATER BALANCE COMPONENTS CUMULATIVE AFTER GERMINATION ET	ES	EP	PREC	PESW
10/12/77	285	0.	SOWING					45.3	45.3	0.0	29.7	16.1
10/13/77	286	6.	GERMINATION					17.3	17.3	0.0	106.3	15.0
10/26/77	299	150.	EMERGENCE, PHINT = 95.									
3/31/78	90	1046.	TERM SPIKELET, VERN DAYS=50.	325.	3.26	0.00	0.01	202.4	99.3	103.1	341.3	20.0
4/19/78	109	1343.	END VEG BEGIN EAR GROWTH	809.	5.93	0.00	0.00	304.2	111.9	192.4	452.3	17.7
5/ 2/78	122	1535.	END EAR GROWTH,EARS= 728.	1176.	5.08	0.00	0.00	368.8	118.6	250.3	552.3	19.5
5/16/78	136	1716.	BEGIN GRAIN FILL,GPSM=15534.	1484.	4.62	0.00	0.00	440.4	128.2	312.2	587.6	15.7
6/11/78	162	2199.	MATURITY,GRAIN WT = 0.0342	1764.	0.62	0.00	0.00	574.0	160.9	413.0	905.6	20.4

YIELD (KG/HA) = 5305. (BU/ACRE)= 79.2 FINAL GPSM= 15534.

MEASURED VALUES ARE: YIELD=4798. KG/HA GRAIN WEIGHT= 35.8 MG GPSM= 13510.
EARS= 847. MAX. LAI= 0.0 FINAL BIOMASS=1571. G/M**2

Figure 1. An example of summary output from CERES-Wheat.

printed. The total user-specified period runoff, drainage and precipitation are printed at the end of the period. An example water balance output is shown in Figure 2.

For the plant growth output record, the date of input is listed along with the model estimates of above-ground biomass, tiller number, LAI, cumulative thermal time, maximum root water uptake, senescent leaf area, water deficit factors, root depth, fraction of assimilate partitioned to plant top, and root length density for each soil depth. Details of the weight of single plant roots, stems, leaf and grain are also output at the specified frequency. An example growth output is shown in Figure 3.

CROP MODEL PERFORMANCE

Data sets of wheat production from several places in the world have been assembled for use in testing and improving CERES-Wheat. Much of the data has come from published sources and the remainder was obtained through personal communication. In all instances, needed details of weather and soil information were usually not available in published reports and were obtained through personal communication. All data sets lacked some detail needed to validate all components of the model. We often used data with good detail in certain processes to calibrate and test those parts of the model.

Our data base was created to be able to test the model in all types of environments where wheat is grown. A data set of about 300 crop years was obtained for testing. These data were from about 25 different sites in the world with a range of latitudes from 36°S in Australia to 50°N in England. At many sites, there was multiple year or multiple treatment information available.

The value of our testing depends to a large degree on the quality of measured data. In practically all data sets used, information was collected for research purposes other than model testing. Thus many desired details are lacking. The minimum requirements for testing were that the needed soils, weather, and management data were available along with some important phase of development and yield.

A scattergram of the estimated yield vs. the measured yields for 168 data sets considered to meet the minimum standards for quality and where nitrogen and other nutrients were assumed non-limited is shown in Figure 4. The bias for the 168 data sets was -104 kg/ha with a standard error of 102 kg/ha. The mean of the absolute difference between estimated and measured yields was 1070 kg/ha with a standard error of 60 kg/ha. Although we wish the model estimates and yield agreed more closely with the field measurements, we believe the large range in yields present in the data set provide a good test of the overall value of the generality of the model for use in the intended applications mentioned earlier in this paper.

Comparison of measured and model estimates of crop growth details during the season has helped in model testing. Figures 5, 6 and 7 show comparisons of seasonal changes in LAI, biomass and tiller number, respectively, for selected tests. In each test it is apparent that considerable experimental variation existed in the measurements, but the general trends and absolute values in the model agreed reasonably well with the measured data.

WEATHER=BUSHLD77 BUSHLAND - TEXAS 1977 - 1978 PD-2 T-4

	JUL	AVERAGE							PERIOD			SOIL WATER CONTENT WITH DEPTH										TOTAL
DAY	DAY	ES	EP	ET	EO	SR	MAX	MIN	RUNOFF	DRAIN	PREC	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	PESW
8/ 4/77	216	0.5	0.0	0.5	9.9	607.	33.9	16.7	0.00	0.00	0.00	0.23	0.28	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.3
8/11/77	223	0.4	0.0	0.4	8.8	496.	34.4	18.7	0.00	0.00	0.00	0.22	0.28	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.0
8/18/77	230	0.4	0.0	0.4	6.5	489.	28.3	17.6	0.00	0.00	0.00	0.20	0.28	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.7
8/25/77	237	0.3	0.0	0.3	7.2	529.	29.6	17.7	0.00	0.00	0.00	0.19	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.5
9/ 1/77	244	0.3	0.0	0.3	5.8	422.	29.4	18.0	0.00	0.00	0.00	0.17	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.3
9/ 8/77	251	1.9	0.0	1.9	6.2	487.	28.7	15.4	0.00	0.00	24.60	0.25	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.4
9/15/77	258	0.5	0.0	0.5	5.4	454.	27.3	13.1	0.00	0.00	0.80	0.23	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.2
9/22/77	265	0.4	0.0	0.4	6.7	468.	31.7	12.0	0.00	0.00	0.00	0.21	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.9
9/29/77	272	0.6	0.0	0.6	5.9	427.	31.1	12.0	0.00	0.00	4.30	0.21	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.9
10/ 6/77	279	0.3	0.0	0.3	3.9	350.	24.2	9.8	0.00	0.00	0.00	0.20	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.6
10/13/77	286	0.8	0.0	0.8	3.5	395.	20.7	4.7	0.00	0.00	100.00	0.33	0.37	0.35	0.26	0.19	0.20	0.22	0.24	0.00	UUUU	16.1
10/20/77	293	1.6	0.0	1.6	4.0	412.	24.4	2.8	0.00	0.00	0.00	0.27	0.34	0.33	0.28	0.19	0.20	0.22	0.24	0.00	UUUU	15.0
10/27/77	300	1.0	0.0	1.0	2.7	285.	23.2	5.3	0.00	0.00	6.30	0.27	0.33	0.33	0.28	0.19	0.20	0.22	0.24	0.00	UUUU	14.9
11/ 3/77	307	0.5	0.2	0.7	2.7	307.	20.2	3.0	0.00	0.00	0.00	0.25	0.33	0.33	0.28	0.19	0.20	0.22	0.24	0.00	UUUU	14.4
11/10/77	314	0.6	0.3	0.9	2.1	274.	17.7	-0.0	0.00	0.00	4.30	0.25	0.32	0.33	0.28	0.20	0.20	0.22	0.24	0.00	UUUU	14.2
11/17/77	321	0.4	0.5	0.9	2.5	317.	19.9	-1.1	0.00	0.00	0.00	0.23	0.31	0.32	0.27	0.20	0.20	0.22	0.24	0.00	UUUU	13.6
11/24/77	328	0.4	0.5	0.9	1.9	260.	16.7	-3.2	0.00	0.00	0.00	0.21	0.29	0.32	0.27	0.20	0.20	0.22	0.24	0.00	UUUU	13.0
12/ 1/77	335	0.3	0.6	0.9	1.6	226.	13.7	-2.9	0.00	0.00	0.00	0.20	0.28	0.31	0.27	0.20	0.20	0.22	0.24	0.00	UUUU	12.4
12/ 8/77	342	0.7	0.6	1.3	1.8	268.	14.0	-5.4	0.00	0.00	100.80	0.32	0.36	0.34	0.30	0.28	0.25	0.22	0.24	0.00	UUUU	21.6
12/15/77	349	1.2	0.5	1.7	1.7	273.	13.0	-6.6	0.00	0.00	0.00	0.27	0.34	0.33	0.29	0.26	0.26	0.26	0.24	0.00	UUUU	20.4
12/22/77	356	0.8	0.5	1.3	1.4	220.	12.2	-4.4	0.00	0.00	1.50	0.24	0.32	0.33	0.29	0.26	0.26	0.26	0.24	0.00	UUUU	19.6
12/29/77	363	0.5	0.7	1.2	1.4	219.	10.9	-5.4	0.00	0.00	0.00	0.21	0.31	0.32	0.28	0.27	0.26	0.26	0.24	0.00	UUUU	18.7
1/ 5/78	5	0.3	0.4	0.7	0.9	188.	9.0	-6.7	0.00	0.00	0.00	0.20	0.30	0.32	0.28	0.27	0.26	0.26	0.24	0.00	UUUU	18.2
1/12/78	12	0.3	0.6	0.9	1.1	256.	7.4	-7.7	0.00	0.00	0.00	0.19	0.29	0.31	0.28	0.27	0.26	0.26	0.24	0.00	UUUU	17.6
1/19/78	19	0.3	0.5	0.8	1.3	306.	4.3	-11.4	0.00	0.00	0.50	0.18	0.28	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.1
1/26/78	26	0.3	0.2	0.5	0.8	255.	3.0	-10.6	0.00	0.00	3.00	0.18	0.28	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.0
2/ 2/78	33	0.2	0.1	0.4	0.6	315.	0.6	-7.8	0.00	0.00	1.30	0.17	0.28	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	16.7
2/ 9/78	40	0.6	0.3	0.9	1.2	351.	4.8	-5.9	0.00	0.00	10.60	0.15	0.27	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	16.2
2/16/78	47	0.3	0.0	0.3	0.3	342.	-0.2	-9.2	0.00	0.00	8.40	0.21	0.27	0.29	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.0
2/23/78	54	0.6	0.1	0.7	0.7	396.	0.4	-11.5	0.00	0.00	1.50	0.25	0.27	0.29	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.6
3/ 2/78	61	0.5	0.6	1.2	2.2	326.	10.9	-2.4	0.00	0.00	0.80	0.22	0.27	0.29	0.26	0.26	0.26	0.26	0.24	0.00	UUUU	16.8
3/ 9/78	68	0.4	0.7	1.1	1.9	368.	7.2	-7.3	0.00	0.00	0.00	0.20	0.26	0.28	0.26	0.26	0.26	0.26	0.24	0.00	UUUU	16.1
3/16/78	75	0.4	1.6	2.0	3.3	446.	16.7	-1.5	0.00	0.00	0.00	0.18	0.25	0.26	0.25	0.26	0.26	0.26	0.24	0.00	UUUU	14.7
3/23/78	82	0.4	2.4	2.8	3.8	460.	21.8	1.8	0.00	0.00	100.00	0.34	0.37	0.35	0.30	0.26	0.26	0.26	0.24	0.00	UUUU	22.7
3/30/78	89	1.2	2.3	3.5	3.5	479.	17.8	1.8	0.00	0.00	2.30	0.27	0.32	0.32	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.5
4/ 6/78	96	1.0	4.5	5.5	5.5	560.	27.3	6.1	0.00	0.00	0.00	0.20	0.26	0.28	0.27	0.26	0.26	0.26	0.26	0.00	UUUU	16.6
4/13/78	103	0.6	4.5	5.1	5.1	575.	23.2	5.4	8.16	21.15	111.00	0.29	0.33	0.32	0.29	0.26	0.26	0.27	0.27	0.00	UUUU	21.2
4/20/78	110	0.5	4.8	5.3	5.3	617.	23.8	4.5	0.00	2.65	0.00	0.22	0.27	0.28	0.27	0.26	0.26	0.26	0.26	0.00	UUUU	17.3
4/27/78	117	0.5	4.5	5.0	5.0	618.	22.4	4.8	0.00	5.87	100.00	0.31	0.35	0.33	0.29	0.27	0.27	0.27	0.27	0.00	UUUU	23.1
5/ 4/78	124	0.4	3.4	3.9	3.9	418.	19.6	5.6	1.00	11.67	30.50	0.33	0.36	0.33	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	22.2
5/11/78	131	0.6	3.9	4.5	4.5	579.	19.9	6.3	0.80	0.00	4.80	0.26	0.32	0.31	0.27	0.26	0.26	0.26	0.26	0.00	UUUU	19.4
5/18/78	138	1.0	6.2	7.2	7.2	657.	28.7	10.6	0.00	0.76	100.50	0.34	0.36	0.34	0.31	0.28	0.27	0.26	0.26	0.00	UUUU	24.4
5/25/78	145	0.8	4.6	5.4	5.4	466.	29.0	13.2	1.71	14.92	11.20	0.27	0.32	0.31	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.1
6/ 1/78	152	1.0	4.3	5.3	5.3	548.	25.5	13.2	78.98	1.63	118.30	0.27	0.32	0.31	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.1
6/ 8/78	159	1.5	2.4	3.9	3.9	472.	22.6	12.5	37.40	1.17	88.00	0.32	0.36	0.33	0.29	0.26	0.26	0.26	0.26	0.00	UUUU	22.3
6/15/78	166	1.7	1.5	3.2	8.0	687.	29.0	15.9	0.00	0.67	0.00	0.23	0.33	0.32	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.0
6/22/78	173	0.6	0.0	0.6	9.9	646.	32.1	18.1	0.00	0.00	0.00	0.21	0.32	0.32	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	19.6
6/29/78	180	0.4	0.0	0.4	11.3	630.	35.6	19.6	0.00	0.00	0.00	0.19	0.32	0.32	0.28	0.27	0.26	0.26	0.26	0.00	UUUU	19.3

Figure 2. An example of water balance output for CERES-Wheat.

WEATHER=BUSHLD77 BUSHLAND - TEXAS 1977 - 1978 PD-2 T-4

DATE	JUL DAY	BIO MASS	TILL /SM.	LAI	SUMDTT	TRWU	PSW	ROOT WT	STEM WT	GRAIN WT	LEAF WT	SEN LFA	SW DF1	SW DF2	ROOT DPTH	PTF	ROOT LENGTH VOLUME L1	L2	L3	L4	L5	L6	L7	L8
11/ 1/77	305	7.	230.	0.09	88.	0.04	7.0	0.007	0.000	0.000	0.028	0.	1.0	1.0	43.	0.79	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11/ 8/77	312	13.	230.	0.17	163.	0.10	7.5	0.013	0.000	0.000	0.057	0.	1.0	1.0	61.	0.82	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
11/15/77	319	21.	230.	0.23	218.	0.11	8.9	0.021	0.000	0.000	0.091	0.	1.0	1.0	69.	0.59	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
11/22/77	326	29.	357.	0.34	278.	0.20	8.5	0.033	0.000	0.000	0.126	0.	1.0	1.0	80.	0.63	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0
11/29/77	333	39.	474.	0.47	335.	0.22	8.2	0.042	0.000	0.000	0.170	0.	1.0	1.0	89.	0.65	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0
12/ 6/77	340	50.	544.	0.54	378.	0.25	8.5	0.053	0.000	0.000	0.217	2.	1.0	1.0	96.	0.61	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0
12/13/77	347	57.	618.	0.51	413.	0.58	8.2	0.059	0.000	0.000	0.248	8.	1.0	1.0	98.	0.66	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0
12/20/77	354	63.	694.	0.65	463.	0.58	7.6	0.060	0.000	0.000	0.276	8.	1.0	1.0	105.	0.76	0.5	0.4	0.2	0.0	0.0	0.0	0.0	0.0
12/27/77	361	71.	747.	0.73	497.	0.47	7.6	0.063	0.000	0.000	0.307	9.	1.0	1.0	109.	0.75	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0
1/ 3/78	3	71.	775.	0.74	517.	0.45	7.4	0.061	0.000	0.000	0.307	9.	1.0	1.0	109.	0.81	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0
1/10/78	10	85.	823.	0.68	557.	0.45	7.8	0.067	0.000	0.000	0.370	18.	1.0	1.0	116.	0.73	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1/17/78	17	85.	832.	0.43	571.	0.36	7.8	0.064	0.000	0.000	0.371	29.	1.0	1.0	116.	0.75	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1/24/78	24	85.	834.	0.36	582.	0.35	7.6	0.062	0.000	0.000	0.372	33.	1.0	1.0	116.	0.75	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1/31/78	31	86.	835.	0.28	585.	0.34	7.6	0.060	0.000	0.000	0.373	37.	1.0	1.0	116.	0.77	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/ 7/78	38	86.	835.	0.33	604.	0.32	7.3	0.058	0.000	0.000	0.372	37.	1.0	1.0	116.	0.82	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/14/78	45	88.	840.	0.32	608.	0.35	7.4	0.057	0.000	0.000	0.382	37.	1.0	1.0	116.	0.80	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/21/78	52	88.	840.	0.31	608.	0.34	7.5	0.055	0.000	0.000	0.384	38.	1.0	1.0	116.	0.80	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/28/78	59	103.	900.	0.41	648.	0.39	7.8	0.063	0.000	0.000	0.449	39.	1.0	1.0	120.	0.77	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
3/ 7/78	66	114.	943.	0.48	673.	0.34	8.0	0.070	0.000	0.000	0.498	41.	1.0	1.0	126.	0.71	0.6	0.6	0.2	0.1	0.0	0.0	0.0	0.0
3/14/78	73	150.	1035.	0.77	728.	0.29	8.8	0.107	0.000	0.000	0.653	41.	1.0	1.0	137.	0.62	0.8	0.8	0.3	0.1	0.0	0.0	0.0	0.0
3/21/78	80	200.	1074.	1.44	794.	0.31	8.4	0.168	0.000	0.000	0.871	41.	1.0	0.9	149.	0.65	0.8	1.3	0.6	0.2	0.1	0.0	0.0	0.0
3/28/78	87	290.	1155.	2.65	868.	2.49	8.1	0.269	0.000	0.000	1.260	41.	1.0	0.9	165.	0.62	1.5	1.8	0.8	0.3	0.1	0.0	0.0	0.0
4/ 4/78	94	445.	788.	4.50	67.	2.32	0.7	0.353	0.071	0.000	1.863	41.	1.0	1.0	188.	0.80	2.2	2.3	1.0	0.3	0.2	0.1	0.0	0.0
4/11/78	101	615.	724.	5.53	178.	3.71	0.9	0.439	0.348	0.000	2.325	55.	1.0	1.0	210.	0.80	2.8	2.8	1.2	0.4	0.2	0.1	0.0	0.0
4/18/78	108	809.	728.	5.93	281.	3.58	1.0	0.536	0.870	0.000	2.647	80.	1.0	1.0	210.	0.80	3.5	3.2	1.4	0.5	0.2	0.1	0.0	0.0
4/25/78	115	1020.	728.	5.40	84.	4.58	1.4	0.604	1.833	0.000	2.602	104.	1.0	1.0	210.	0.85	4.0	3.6	1.6	0.5	0.2	0.1	0.0	0.0
5/ 2/78	122	1175.	728.	5.03	7.	4.80	1.4	0.651	2.560	0.000	2.551	119.	1.0	1.0	210.	0.90	4.4	3.8	1.7	0.5	0.2	0.1	0.0	0.0
5/ 9/78	129	1328.	728.	4.78	70.	4.75	1.4	0.669	3.248	0.000	2.524	130.	1.0	1.0	210.	0.90	4.3	3.7	1.6	0.5	0.2	0.1	0.0	0.0
5/16/78	136	1500.	728.	4.60	2.	2.75	1.4	0.698	3.747	0.303	2.471	138.	1.0	1.0	210.	0.89	4.5	3.8	1.7	0.5	0.2	0.1	0.0	0.0
5/23/78	143	1598.	728.	4.46	133.	4.82	1.4	0.712	3.701	0.829	2.419	144.	1.0	1.0	210.	0.89	4.5	3.8	1.7	0.5	0.2	0.1	0.0	0.0
5/30/78	150	1674.	728.	3.73	268.	4.74	1.4	0.715	3.509	1.401	2.369	176.	1.0	1.0	210.	0.90	4.4	3.7	1.6	0.5	0.2	0.1	0.0	0.0
6/ 6/78	157	1727.	728.	1.89	389.	4.62	1.4	0.708	3.191	1.978	2.341	256.	1.0	1.0	210.	0.93	4.3	3.6	1.6	0.5	0.2	0.1	0.0	0.0

Figure 3. An example of plant growth output for CERES-Wheat.

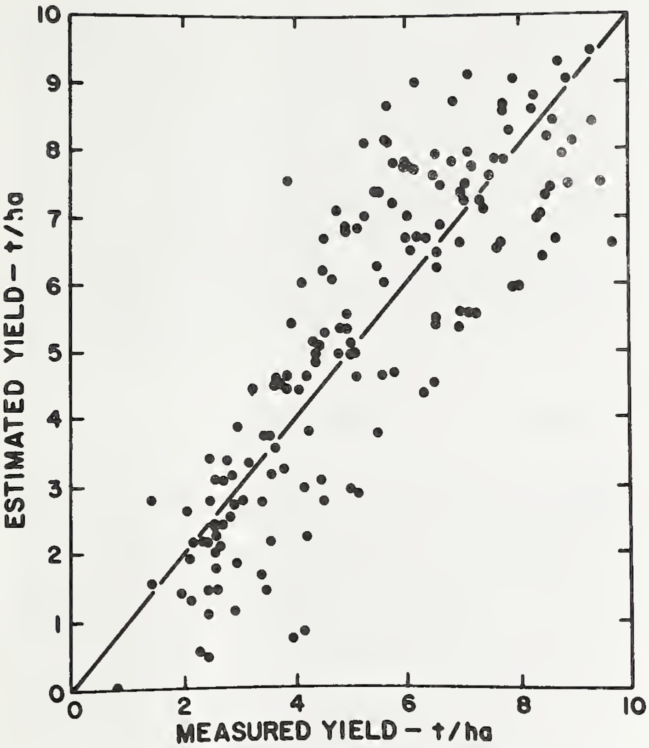

Figure 4. Estimated versus measured yields for individual crop-year data sets.

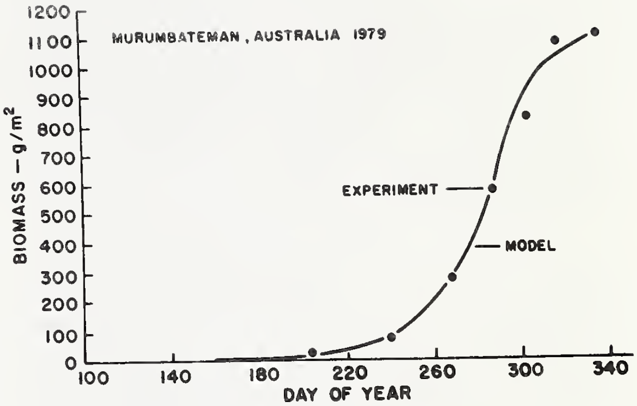

Figure 6. Seasonal changes in total wheat biomass for data from Murumbatem, Australia.

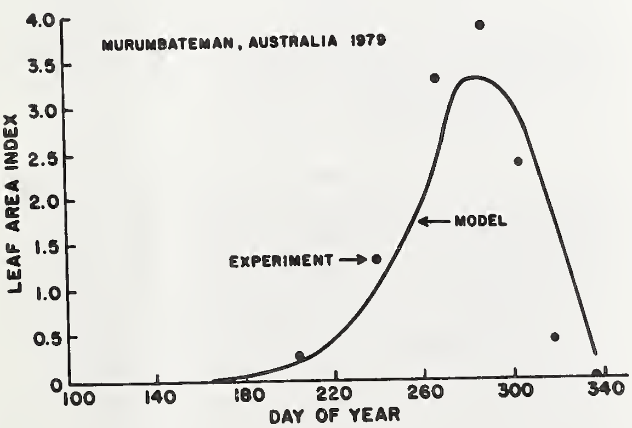

Figure 5. Seasonal changes in leaf area index for data from Murumbatem, Australia.

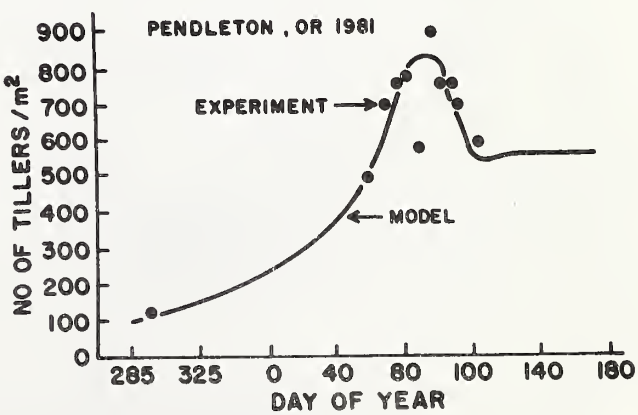

Figure 7. Seasonal changes in numbers of wheat tillers for data from Pendleton, Oregon.

Comparison of measured and model estimates of the average soil water content in the total profile for a wheat crop at Phoenix, Arizona, is presented in Figure 8. This comparison demonstrates the model capability to estimate water balance values reasonably well. There were no measurements of root length for this test, so errors in estimating root length could contribute to some of the error in estimating the soil water distribution.

Another valuable type of testing of CERES-Wheat was a sensitivity analysis performed by the Statistical Reporting Service (Larsen, 1981). That report, based on results from an analysis of an early version of CERES-Wheat, pointed out several critical functions in the model and made recommendations for improvement. Several of the weaknesses found in the study had already been recognized from other testing and improvements were made where possible.

The Foreign Agricultural Service has conducted operational tests of the model for large area yield estimation. That effort, primarily by Tom Hodges

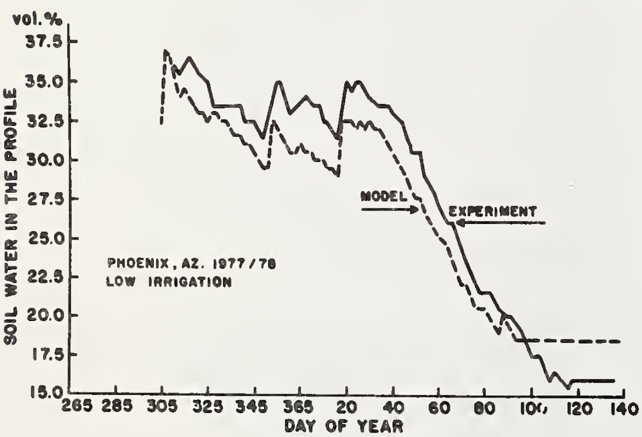

Figure 8. Measured and model estimates of seasonal total soil water (to 150 cm) with wheat at Phoenix, Arizona.

and Pat Ashburn, has helped us recognize a few programming errors that had gone unnoticed in other testing operations. Ashburn (personal communication) stated that the phasic development part of CERES-Wheat had estimated crop stages within a few days of reported dates for test regions in Europe and Asia. The yield estimates were also within reasonable agreement of reported yields for the region.

DISCUSSION AND CONCLUSIONS

The development of CERES-Wheat has been exciting and challenging. It is exciting because of the interest shown by the user community in models with a stronger scientific base. It is challenging because of the diversity of information from different scientific disciplines required to provide a general, balanced model sensitive to the major factors influencing yield. Although the model tests have demonstrated its usefulness for various purposes, several limitations still exist. A major limitation for large area yield estimation is the availability of good input information regarding spatial distribution of precipitation and soil properties. Errors in those inputs can cause large errors in yield, especially in areas where water deficits are common.

There are undoubtedly several parts of CERES-Wheat that need improvement as testing of the model has demonstrated. Improvement of some critical parts of the model is impaired by lack of available information. The formulation and testing of this model has generated several ideas about needed research and has created a demand for data not usually collected in experiments. An outstanding example of one future research need deals with shoot-root partitioning and the fate of assimilate partitioned

to roots. While many studies have measured root-shoot weights through a season, the root weights may not reflect the amount of assimilate partitioned to them because of losses through exudation, sloughing and respiration. Several papers dealing with this problem have demonstrated that more than half the assimilate partitioned to roots is not recovered from the roots when observed a few days after C^{14} labeling, but rather is found in the soil. In CERES-Wheat, the partitioning principles had to be based on a few data sets where roots and shoots were measured, and this possible source of error could contribute to some of the error in yield estimation. Also, the dynamics of root growth into soils is poorly understood and needs more research, but the research needs to be done in the context of whole crop measurements to be useful in models.

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245

CHAPTER 11. THE DEVELOPMENT OF WINTER WHEAT: A PHYSICAL PHYSIOLOGICAL PROCESS MODEL

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INTRODUCTION

This paper provides a synopsis of activities leading to the development of the simulation model WINTER WHEAT. Modeling activity was begun in response to the need for a capability to predict wheat yields in the United States and in other parts of the world. From the outset, however, we envisioned a broad range of applications, including fertilization, irrigation, tillage and pest management, breeding feasibility studies and a variety of possible environmental impact assessment studies. All of these applications have in common the need for a model which predicts wheat growth, development, and yield responses to exogenous variables. They dictate a physical/physiological process level dynamic simulation model. We expected that the model development would help guide our experimental research and that expectation has been realized.

The work began with a review, by Dr. Jim Haynes, (Earthsat Corp.) of progress with a "phenological" model. He and his colleagues had made much progress over a period of years, but the review revealed a number of limitations inherent in phenological models. The model provided no treatment of soil processes, and so it tended to be rather site specific. It bundled developmental processes, including stress effects which may delay development, in with organ abortion, with the result that rates of appearance of and numbers of organs were unreliable under conditions of water, nutrient and carbohydrate stress. Photosynthesis and respiration were not treated explicitly and so grain dry weight estimates under (photosynthate) source limiting conditions were often in error. Personnel at Earthsat and in other agencies felt that ARS could address these problems.

Our objective is to identify and assemble the factors determining winter wheat growth and yield in a format which will aid system design (breeding and new cultural practices, and combinations thereof), crop management decision making at the farm level, and yield forecasting. We see this effort as an ongoing process of identifying and mathematically testing (sensitivity analysis) the factors determining wheat growth and yield, and of synthesis (modeling) in which these factors are assembled for rational use by agronomists and farm managers.

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We began with a literature review and consultations among ourselves and with other researchers outside the modeling group. We believed that users would be able to provide Class "A" weather station and solar radiation data. We also assumed that available soil information would include bulk density, soil water desorption, and hydraulic conductivity data.

To address the problem of dry matter accretion under source limited conditions, we decided to follow the lead of GOSSYM (Baker, et al., 1983) and numerous other crop simulation models, by making WINTER WHEAT a materials balance model. To overcome the problem of site specificity, RHIZOS (Lambert, et al., 1976) was incorporated to simulate below ground processes. RHIZOS was used in its two-dimensional form because winter wheat is planted in rows, up to 35 cm wide, (six vertical columns in the RHIZOS matrix), and the canopy may never close under dryland conditions. Contributing to both of these decisions was the recent industry survey of McKinion (1982) showing that within a couple of years after project initiation, a materials balance model of this type with daily time steps and 120 element soil arrays could be executed on microcomputers requiring minutes to simulate a season's growth.

The first result of the consultations was a set of flowcharts representing major aspects of the physiological processes in winter wheat. The physiological, climate and soil processes were written in subroutine modules (Figure 1). In the following paragraphs we consider the major concepts of WINTER WHEAT in subroutine order.

The processes to be considered can be identified in Figure 2. Solar radiation and carbon dioxide are absorbed by

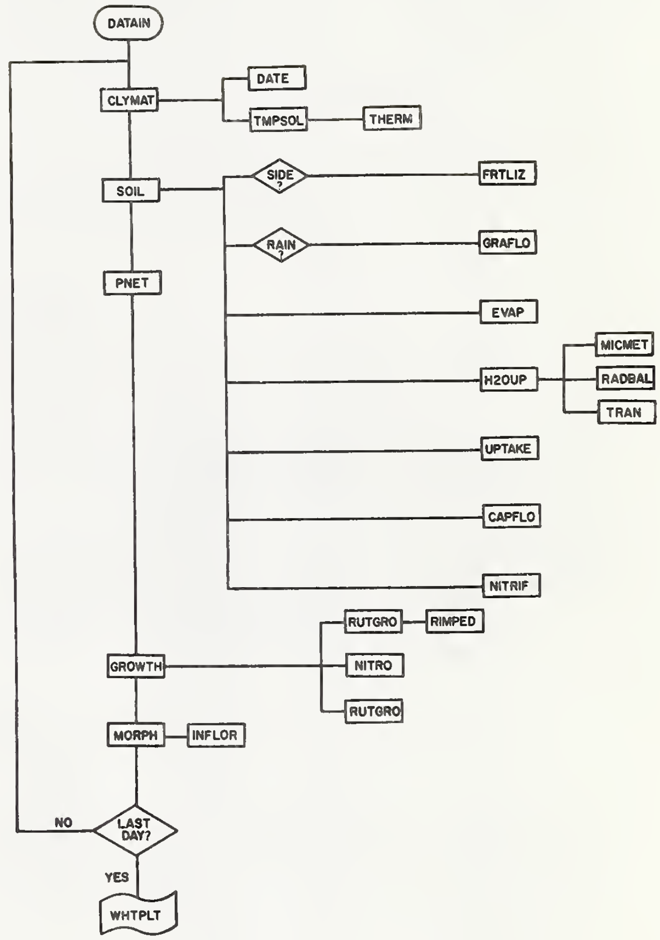

Figure 1. The subroutine of WINTER WHEAT. Acronyms reflect the following: DATAIN (data in), CLYMAT (climate), SOIL (soil), PNET (net photosynthesis), GROWTH (growth), MORPH (morphogensis), INFLOR (inflorescence), WHTPLT (wheat plant), DATE (date), TMPSOL (soil temperature), THERM (thermodynamics), FRTLIZ (fertilizer), GRAFLO (gravity flow), EVAP (evaporation), H2OUP (water uptake), MICMET (micrometeorology), RADBAL (radiation balance), TRAN (transpiration), UPTAKE (uptake), CAPFLO (capillary flow), NITRIF (nitrification), RUTGRO (root growth).

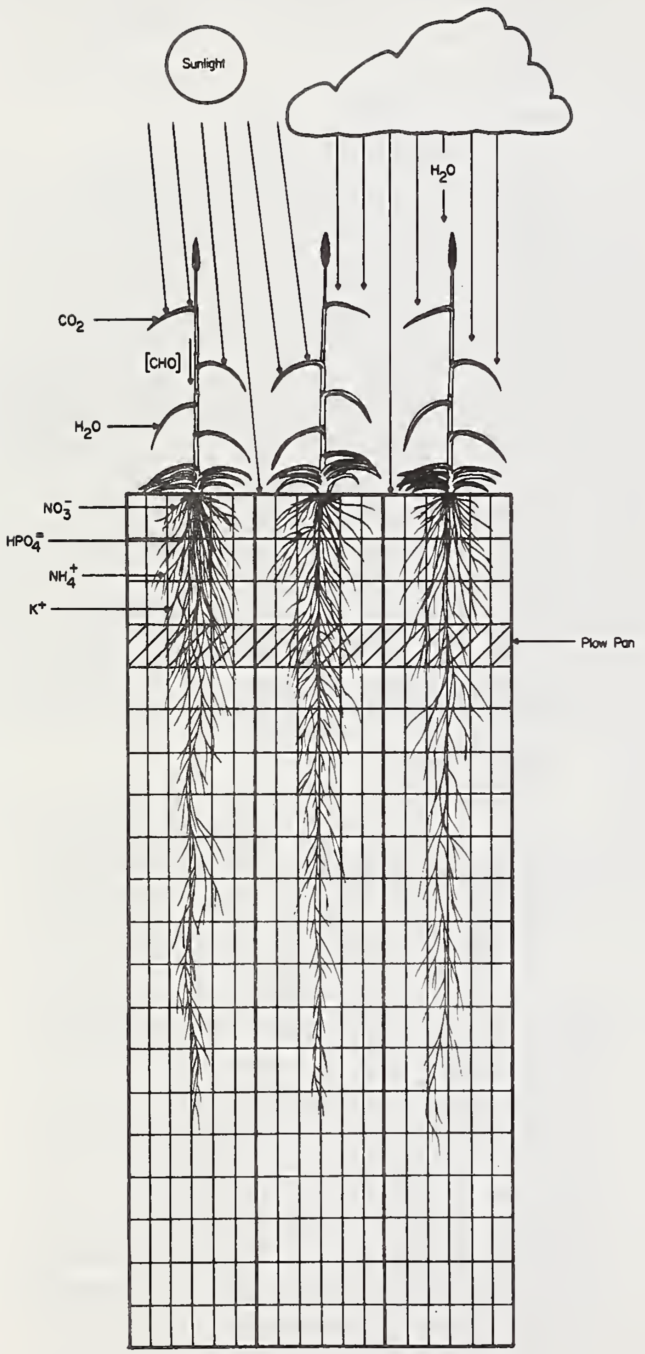

Figure 2. The wheat system.

the crop canopy. Some of the absorbed energy is converted into latent heat, and water is transpired by the crop.

Time increments of simulated light capture, photosynthate production and water consumption are calculated on a canopy ground area basis. The estimated carbon dioxide fixed is converted to dry matter, divided by plant population (per unit ground area) and distributed to the plant's growing organs. A continuous inventory of simulated above ground organs is maintained. Below ground, a two-dimensional root distribution is simulated. Root dry matter in each cell of the (RHIZOS) matrix is added to a pool of young roots with each iteration of the model. After a certain threshold mass (length) of roots has accumulated in a cell, further dry matter increments may be distributed to either of three adjacent cells, right, left or below. Amounts distributed to each of these cells is normalized with respect to root penetration resistance, water content, and soil oxygen content. Dry matter is allocated to a particular cell in the matrix when the quantity of older roots in the parent cell exceeds a threshold amount. Also, in each cell, some root dry matter is calculated to be lost (sloughed) each day. Water and nutrients are simulated to flow more rapidly into the younger roots, with the rate of flow proportional to the biomass of young roots in each cell of the matrix. Soluble nutrients may be in short supply in the plant, if water is being drawn from cells in the soil matrix which are low in nutrients. Both soluble nutrients and nutrients adsorbed on soil colloids are assumed to be taken up actively. Active uptake, however, becomes relatively less important as the leaf canopy develops and transpiration increases.

Rainfall and irrigation water arriving at the soil surface is assumed to be distributed vertically. Each layer is wet from top down, to field capacity,

either until all layers are at field capacity, or until all the water is taken by the upper layers.

More details on the concepts in WINTER WHEAT are presented in Baker, et al., (1981), Morgan, et al., (1982), Whisler, et al., (1982), and in the discussion below. The subroutines are called from a MAIN program. MAIN also performs a few calculations pertaining mostly to input/output. Data describing climate, the soil and the initial status of the plant are read in before the subroutines are called and the simulation of the crop begins. MAIN cycles daily (Figure 1), although the model will soon be rewritten to cycle on hourly time steps during the daylight hours. SOIL calls most of the RHIZOS subroutines. They produce soil water potentials and the amount of nitrate taken up by the plant each day. The daily increment of dry matter produced is calculated in PNET and is distributed to the various plant growing points in the subroutine GROWTH. GROWTH, in turn, calls RUTGRO, a subroutine which calculates root growth. GROWTH also calculates carbohydrate stress and calls NITRO which calculates nitrogen stress and allocates, to the various plant parts, the nitrogen which has been taken up. All morphogenetic processes, as well as records of the abortion tillers and grain, are handled in MORPH.

THE SUBROUTINES

CLYMAT

Temperature and solar radiation data are manipulated in CLYMAT, and canopy light interception is calculated. Interception is defined as the product of two terms. The first is a ground cover term, simply the maximum leaf length divided by the row width. The second (TERM2) is a Beer's law type of canopy light attenuation term based on leaf area index.

$$TERM2 = 1 - \exp(-.4*LAI),$$

where .4 is an extinction coefficient from Monteith (1965).

TMPSOL

CLYMAT calls the subroutine TMPSOL which calculates the daily and hourly average, maximum and minimum soil temperature at regularly specified depths, e.g. 10 cm, starting at the surface. Hourly values are obtained via a sine wave distribution. The Fourier heat transfer function with thermal diffusivity from the subroutine THERM (Acock, et al., 1985) is used.

THERM

THERM is called by TMPSOL. Thermal conductivity of each soil layer is calculated from soil texture, organic matter and water content in each layer.

SOIL

SOIL and the subroutines called from it are part of a collection of subroutines called RHIZOS (Lambert, et al., 1979). RHIZOS was designed to work in any crop simulation model. It provides the overall model with an estimate of ammonium and nitrate-nitrogen uptake rates, soil and plant water potentials, and an estimate of the root sink strength for photosynthate and nitrogen compounds. A two dimensional model, RHIZOS considers a cross section of the soil under one row. Both dimensions of the section are variable, the width being row width and two meters being the depth

(typically). This section is 1 cm thick and it is assumed to be longitudinally representative of the row. It is subdivided into K columns and L layers, where K and L are, typically, 6 and 20, respectively. RHIZOS keeps a continuous record of the amount of water, nitrate, ammonium nitrogen, organic matter and root material in each cell of the matrix. An age vector of root mass is maintained and used to estimate root growth and water uptake.

FRTLIZ

If fertilizer is to be added on a given day, the subroutine FRTLIZ is called. Fertilizer may be banded or applied at any depth. FRTLIZ locates the fertilizer in the soil matrix as specified.

GRAFLO

If rainfall or irrigation occurs, GRAFLO simulates the distribution of water vertically as described earlier. Ammonium ions are assumed to be adsorbed on soil colloids which are assumed to be stationary. Nitrate nitrogen, on the other hand, is assumed to be in solution and to move with the soil water. Thus, excessive rains or irrigation may elute nitrate-nitrogen out of the soil profile, because the bottom boundary is ordinarily a sieve.

EVAP

Potential evaporation from the soil surface is calculated in the subroutine EVAP. This subroutine uses part of the logic presented by Ritchie (1972), including the modified Penman equation. Potential evaporation rates are reduced under the canopy due to shading effects.

H2OUP

The subroutine H2OUP calls three other subroutines, MICMET, RADBAL, and TRAN to calculate transpiration by two methods which are allowed to converge via an iterative process. First, the fractions of solar and sky radiation absorbed by live and dead leaves in the canopy are calculated. Then, the air temperatures at two meters and at the crop surface are calculated. H2OUP calls MICMET to calculate the crop boundary layer resistance. Then, RADBAL uses this resistance to calculate live and dead leaf temperatures. An energy balance is performed, and latent heat loss from live leaves is estimated. H2OUP then calculates plant water potential and calls TRAN. TRAN estimates root (from root length and age) and soil resistance to water flow and then calculates transpiration from the plant-soil pressure gradient and the resistances. This increment of water loss is used to calculate relative water content and plant water potential. If the two estimates of latent heat loss differs by more than five percent, the computer returns to RADBAL for another estimate based on a value of stomatal resistance obtained from the new leaf water potential. TRAN is then called to obtain a new estimate of water uptake using the new plant water potential. Seldom are more than three iterations required for convergence between the two methods. To summarize, H2OUP provides the model with estimates of water uptake, plant water potential and canopy temperature. These variables are used in calculating photosynthesis, respiration, organ growth and plant development.

UPTAKE

This subroutine calculates withdrawal

of water and nitrate from the (two-dimensional) soil profile. The rate of withdrawal from each soil cell depends on the root density within the cell, the age distribution of those roots, and the water status of the cell, characterized by the soil water potential and diffusivity. Evaporation occurs only from the surface cells.

The total root withdrawal of water is made equal to the daily transpiration rate calculated in H2OUP. The time step used in UPTAKE is variable. It is dependent primarily on grid size and on hydraulic characteristics of the soil. This time step will be discussed under CAPFLO. UPTAKE is called (several times) during daytime only.

Nitrate is assumed to be completely dissolved in the soil solution and is assumed to move by mass flow. Passive uptake proportional to concentration occurs in UPTAKE. Additionally, a Michaelis-Menten type calculation of active nitrogen uptake is made.

CAPFLO

Uptake of water by active roots and evaporation from the soil surface create water potential gradients within the soil profile. Simulated redistribution of water by capillary flow is done using an explicit form of a finite difference approximation of Darcy's law. CAPFLO is called subsequent to each call of UPTAKE. During the daytime both subroutines are normally called four or five times. The idea is that water uptake and subsequent redistribution occur during daytime. During nighttime CAPFLO is also called four or five times, without UPTAKE being called. As stated, nitrate present in the soil water moves by mass flow along with the water that is redistributed.

No external driving inputs to CAPFLO are needed. Volumetric water content and nitrate concentration matrices are used. Soil water potential is calculated for later use. Two curves describing hydraulic properties of the soil are needed: viz, diffusivity and water potential as functions of soil water content. Figures 3 and 4 illustrate the relationships used in portions of our study (Lambert and Baker, 1985).

One soil boundary condition is: no water movement occurs across the planes below the left row or midway between the rows, due to symmetry. Several possibilities exist for the bottom boundary condition. Time-varying potential, constant flux, constant potential and one-way flow are feasible conditions. Selection of the bottom boundary condition will depend on available data and field conditions.

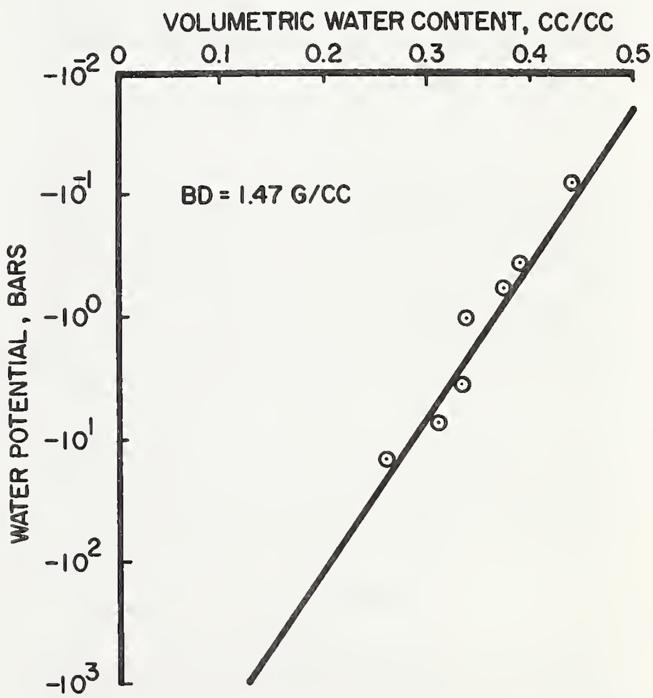

Figure 3. A typical soil water research curve.

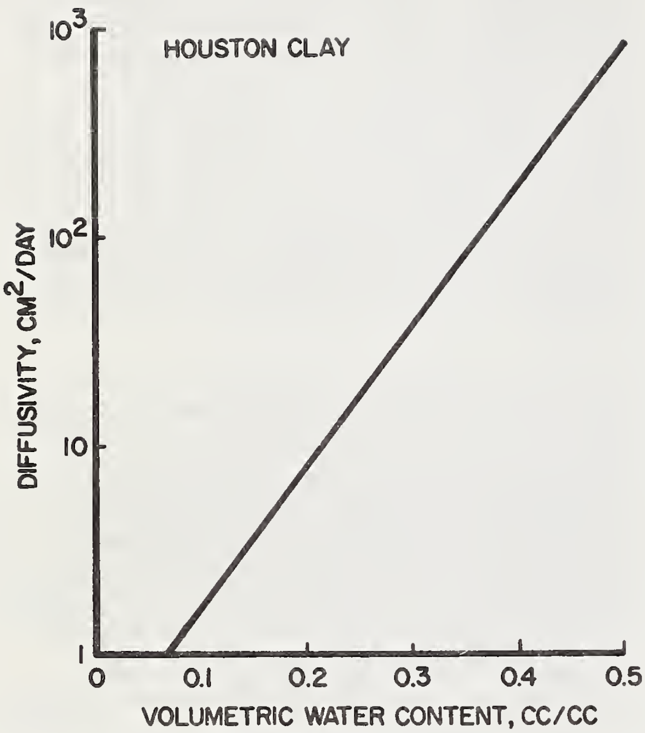

Figure 4. Typical relationships used in hydraulic diffusivity versus water content curve.

The time increment for CAPFLO is critical. Increments which are too large cause oscillations and overshoot. Both indicate instability. With any transient differential equation, e.g. Darcy's law, which is discretized in space for finite difference analysis, a relation exists between the size of the finite space increments and the size of the allowable time step. De Wit and van Keulen (1972) indicated that for capillary water flow in soil:

$$\Delta t \leq (\Delta x)^2/D$$

where Δt = time increment
Δx = smallest space increment, and
D = maximum soil water diffusivity.

For Δx = 5 cm, and Θ_{max} = 0.43 cm^3 H_2O per cm^3 soil, where ψs = -0.13 bars, K = 0.0786 cm/day, and D = 302 cm/day, $\Delta t \leq 0.08$ days was calculated according to the above equation. We have been using 0.1 days for a time increment with only minor instability problems.

NITRIF

Mineralization and nitrification of organic nitrogen are calculated in a simple subroutine model from Kafkafi, et al. (1978). These process rates are functions of soil temperature and soil water content.

PNET

As noted earlier, WINTER WHEAT is a materials balance model, i.e., with each day an increment of dry matter is produced and distributed to the growing points in the plant. The end point yield, then, is the dry weight of the grain. First, canopy photosynthesis is calculated as a function of light intensity. The data base for this was obtained in SPAR (naturally lit, soil-plant-atmosphere controlled-environment research units) experiments. The plants were grown in a Norfolk sandy loam topsoil in a row crop configuration, with natural sunlight. The soil was heavily fertilized and well watered. Measurements were made at several crop developmental stages. In this way, the decline in photosynthetic efficiency with crop senescence was characterized.

Leaf water potential, estimated in H2OUP, is used to form a water stress reduction factor (PTSRED) for photosynthesis. This factor is based on SPAR data (unpublished) showing direct, short-term, effects of water stress on photosynthesis, and the effects of

water and nitrogen stress on rates of canopy senescence. Next, the reduction factor for leaf nitrogen concentrations below two percent is calculated.

Gross photosynthate production on a per plant basis is calculated as follows:

PPLANT = PSTAND*INT*PTSRED*PTSN*SEN*POPFAC,

where PSTAND is the well-watered increment of photosynthesis, INT is the fraction of incident light captured by the crop canopy, PTSRED, PTSN and SEN are reduction factors for water stress, nitrogen stress and senescence, respectively, and POPFAC converts mg CO_2/dm^2 ground area to g CO_2/plant. Respiration was also measured over a range of temperatures in the (above) photosynthesis experiments. The data were summarized to permit calculation of respiration in PNET as a function of temperature and plant weight.

Finally, the dry matter increment available for growth is calculated by subtracting the respiratory loss from the photosynthate produced and multiplying the result by a constant to convert g CO_2/plant to g CH_2O/plant.

GROWTH

This subroutine calculates potential and actual increments of growth of each of the organs on the plant. (Genetic) potential organ growth rates are calculated from equations summarizing data (unpublished) from SPAR experiments in which plants have been grown with high fertilizer and irrigation inputs at an atmospheric CO_2 concentration of 600 µl/l. Reduction factors to convert potential organ growth rates to actual growth rates were obtained from other SPAR experiments in which organ growth rates were recorded under a range of water, nutrient and carbohydrate stress conditions. Root growth is handled in RUTGRO, a RHIZOS subroutine, which is called twice each iteration from GROWTH.

Growth strategy is as follows:

a) the plant is inventoried and a potential growth rate for each of the organs is calculated as a function of temperature and turgor level, assuming no shortage of photosynthate or nitrogen. A total carbohydrate demand (CD) is calculated as the sum of the potential growth increments of all the plant organs. Plant attributes used in this calculation include organ weights and ages since initiation.

b) after calculation of potential carbohydrate requirements, the NITRO subroutine is called from GROWTH. Its function is to estimate the nitrogen required to assimilate the amount of carbon just estimated for each of the organs. These nitrogen requirements are summed for the vegetative and inflorescence parts, and the sums are used in the denominators of nitrogen supply/demand ratios to estimate the maximum fractions of the carbohydrate uptake potentials that can be assimilated, considering nitrogen limitations. This, then, is a reduced or refined estimate of potential organ growth increments.

c) A carbohydrate supply/demand ratio is calculated as follows:

CPOOL = PN + RESC

CSTRES = CPOOL/CD

where CPOOL is the total available pool of carbohydrate from this increment of photosynthate production, plus reserves carried in from earlier

iterations, and CSTRES is the carbohydrate supply:demand ratio.

d) actual growth of each organ on the plant is then calculated as the product of potential growth multiplied by CSTRES. This partitions photosynthate to each organ on the plant in proportion to its contribution to total demand, except that grains are allowed to receive their full requirement first, if sufficient carbohydrate is available for grain growth. Anything beyond that is partitioned to the vegetative parts, including roots.

RUTGRO

This subroutine calculates potential and actual dry matter in the various parts of the root system. It also provides the above ground portions of WINTER WHEAT with an estimate of the water potential of the rooted portion of the soil profile which is used in estimating plant water potential.

A potential growth rate is computed for each cell in the RHIZOS matrix as a function of temperature and the biomass of root material in that cell in the age category capable of growth. This quantity has the dimensions of grams weight increase/day/gram of growing tissue, and, thus, it operates as an exponent. This potential increment in root dry weight for each cell is decremented by a ratio obtained from the root impedance values calculated for the particular cell, the two cells to the right and left, and the cell immediately below. The ratio of root growth under mechanically impeded conditions to that without impedance is calculated in RIMPED as a function of bulk density and volumetric water content in that region. The data base for this calculation is found in Campbell, et al. (1974) and Taylor and Gardner (1963). The reduced potential root growth increments are summed to obtain a total metabolite sink strength in the root system for use in computing the metabolic stress parameters discussed above in GROWTH.

Returning to RUTGRO, with an increment of photosynthate from GROWTH, each cell receives a fraction of the total available to the root. If the mass of root dry matter in the (particular source) cell is greater than a threshold amount, the dry matter increment is distributed to the source cell and to the cells to the right, left and below. Distribution factors are obtained by normalizing the soil water potential and root impedance values for these four cells. Thus, total root growth is decreased and the direction of root growth is influenced by physical impedance.

MORPH

The subroutine MORPH uses environmental input information, especially temperature, along with internal estimates of physiological stress to determine the rate of morphological development of the average wheat plant. Thus, the phenology of the crop is simulated in MORPH. The operative definition of the term "stress" is: any factor which reduces organ growth below its genetic potential at a given temperature and turgor level. The mathematical definition of stress, as outlined in GROWTH and NITRO, is the supply:demand ratios for nitrogen and carbohydrate. The key idea of this subroutine is that organ numbers, for example, tillers and florets, are resultants of the rates of initiation, dependent mainly on temperature, and abortion, dependent primarily on physiological stress.

The timing of some discrete morphological events is based on the accumulation of heat units defined as centigrade degrees above zero. For example, tillering begins when 170 units have accumulated following emergence and ends at jointing (300 units). Heat unit accumulation for the other events begins January 1. Spike differentiation begins at 125 units. Jointing begins at 300 and ends at 500 units. Booting begins at 500 and ends at 600 units when heading occurs. Anthesis, for a particular spike, is calculated as the time that spike differentiation began plus a time increment based on the running average temperature calculated since differentiation began, plus the time difference from the jointing of the first spike to the spike under consideration. Thus, anthesis for the various spikes is separated in time partly due to the time spread in the jointing of the various stems.

From the time of emergence, secondary roots are initiated at a rate depending on the running average temperature. A given secondary root will be aborted immediately if soil water potential in the rooted portion of the soil profile is below -1 bar. Each day, after spring green up, if the mean number of secondary roots per stem is less than four, or if the plant water potential is below -20 bar, the youngest tiller on the plant is aborted.

New leaves are associated with each tiller at a rate depending on the running average temperature since the last leaf initial. A maximum of nine leaves per tiller is allowed at present. At spring green up all the leaves are aborted and a new leaf canopy is built. Thus, we assume that the function of fall grown leaves is to provide photosynthate to nourish fall tillers and for nutrient and energy storage in the crown.

INFLOR

On the day head differentiation begins, MORPH calls INFLOR which simulates the development of the inflorescence.

Little is known about the time spread among tillers in spike differentiation, therefore, we have arbitrarily chosen to use a time lag for each of the tillers, equal to the time lag in first leaf initiation. On a given tiller, the following describes briefly the simulated course of events in differentiation. First, the rachis is built. Next, floret initiation and development occur. Finally, the computer examines the three dimensional spike matrix, and may abort a number of florets in the age window of vulnerability. The most vulnerable florets are always the youngest in the spike. The number to be aborted is a function of physiological stress. Physiological stress is defined as the product of the supply demand ratios of translocatable carbohydrate and nitrogen in the plant.

The calculated length of the rachis is a function of leaf nitrogen concentration. The length of the time period from double ridge to anthesis is calculated as a function of temperature. Rachis development takes 20 percent of that time. After rachis development, floret initiation begins with the spikelet closest to 40 percent of the way up the rachis. New florets may be initiated within a spikelet at half the rate at which they may appear at new joints in the rachis. The florets may actually be initiated more slowly as a result of delays due to physiological stress.

Information pertaining to the status of the florets in the head are contained in two-dimensional (joints in the rachis and florets in the spikelets) matrices. These matrices include dry

weight, nitrogen content, age, and developmental status of each of the florets. The notation used in diagramming the heads for the output is presented in Figure 5.

SUMMARY

WINTER WHEAT is a materials balance physical/physiological process oriented dynamic model which simulates the growth, development and yield of a "typical" wheat plant in a particular field. It calculates the time of appearance and keeps a record of the mass, nitrogen content and age of each organ on the plant. The initiation of secondary roots and the extension of the roots through the soil profile are calculated as functions of temperature, soil water, mechanical impedance and the availability of photosynthate. Rates of photosynthesis and respiration are empirically based on measurements in intact wheat crop canopies in which temperature, solar radiation, water stress and nitrogen stress have been systematically varied. Stress is defined to be anything which impedes organ growth. Tiller and floret abortion are calculated as functions of stress. Transpiration from the plant and evaporation of water from the soil surface are calculated via an interactive scheme involving the energy balance and pressure gradients. Uptake of mineral nutrients occurs both as a result of passive entrainment in the transpiration stream and a Michaelis-Menten approach calculation of active uptake.

The WINTER WHEAT model has evolved as a result of discussions and searches of unpublished data sets among the authors. It has identified specific controlled environment and field experiments, which have been done and summarized to provide system constants and rate equations in the model. This process has taken approximately seven years with varying degrees of input by the authors and it will probably continue for several years to come, as more is learned about the wheat plant and the wheat ecosystem. Most of the deficiencies identified in an earlier description of the model (Baker, et al., 1981) have been addressed in the research and in the code.

```
   *I
    I*
   *I
    I**           I
  **I             I*
    I**          *I
  **I             I*            I
    I***         *I            *I            I
 ***I             I**           I*            I*
    I***        **I            *I            *I
 ***I             I**           I**           I*
    I***       ***I           **I            *I
****I             I***          I**           I**
    I****      ***I           **I           **I
 ***I             I***          I***          I**
    I***       ***I           **I          ***I
 ***I             I***          I**           I**
    I**         **I           **I           **I
  **I             I**           I**           I**
    I**         **I            *I            *I
  **I             I*            I*            I
    I*           *I             I             I
   *I             I             I             I
    I             I             I             I
```

Figure 5. Typical WINTER WHEAT inflorescences representations for a plant with a mainstem (left) and three tillers. I, and * represent rachis joints and florets respectively.

ACKNOWLEDGMENTS

The authors wish to acknowledge the work of G. S. McMaster and S. B. Turner in coding much of the model described here. We also wish to acknowledge valuable advice and consultation from Dr. J. A. Morgan concerning the physiological processes.

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CHAPTER 12. DEVELOPMENT OF EARLY WARNING MODELS

G. O. Boatwright, F. W. Ravet and T. W. Taylor[1]

INTRODUCTION

USDA policy is to provide American farmers and commodity analysts with timely information concerning world and national agricultural activities. In response to initiatives issued by the Secretary of Agriculture, meteorologically driven stress models were developed to provide early warning of actual or potential plant stress due to water deficits, excessive quantities of water, and adverse temperature conditions. The models also provide alerts to indicate that optimal conditions exist for crop production. The models discussed in this chapter have been transferred to USDA-FAS to be used by commodity analysts in the Foreign Crop Condition Assessment Division (FCCAD).

The FAS-FCCAD operational plan calls for the assessment of crop production in foreign areas based on a convergence of evidence from many sources. Traditional sources (such as attache reports, trade reports, foreign government reports, etc.) are used in conjunction with agrometeorological models that infer crop conditions on a global basis. The early warning models were developed to alert crop analysts to potential crop production problem. The models use daily meteorological station and/or I, J gridded data because these data are more timely and generally more readily available than Landsat data. The I, J gridded data (25 by 25 nautical mile cells) are available from the U.S.A.F. Each cell contains daily maximum/minimum temperature, precipitation, snow cover, solar radiation, and evapotranspiration potential estimates. The models filter the data in that they alert analysts only to areas having high probabilities of crop stress. Once potential stress areas or areas with better-than-normal conditions have been identified, analysts can assess the condition more closely using satellite and/or other ancillary data. The models are not intended as stand-alone systems, but rather as alert mechanisms for large area assessments.

Early warning stress indicator models have been developed for wheat, maize, sorghum, and sugar beets. A wheat winterkill model and a wheat yield reduction model have also been developed. A harvest loss model, a soybean stress model, and a stem rust indicator model are under development. Early warning models are interim steps toward the development of more sophisticated yield models similar to those described in Chapters 10 and 11.

Early warning stress models require accurate crop calendar and water budget models because parameter thresholds are crop specific and crop stage dependent. Crop calendar and soil water budget models developed during LACIE were modified and used within the structure of the early warning stress models. Stress indicator model inputs and outputs are similar for all crops.

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MODEL STRUCTURE

Early Warning Stress Indicator Model for Wheat

The wheat stress indicator model developed by Ravet et al., (1979) contains three central components: 1) a crop phenology model, 2) a soil water budget model, and 3) a stress function routine. These models all require daily maximum and minimum temperature and precipitation.

Crop Phenology Model (Component)

The crop phenology model is a modified version of the Robertson Biometeorological Time Scale (BMTS). Robertson (1968) developed the BMTS for tracking phenology of spring wheat in northern latitudes. The model was modified for winter wheat by changing maximum and minimum temperature and daylength coefficients (Feyerherm 1977) and by adding a spring restart subroutine. The spring restart subroutine is based upon the hypothesis that soil temperature is the controlling parameter for spring growth initiation. Personal consultation with D. E. Smika (1977) provided evidence that summing the mean soil temperature above -4°C to a total of 25 degree days would predict spring regrowth initiation. Should the soil temperature fall below -4°C, the summation is set to zero and started over. Heuer, et al., (1978) states that this is the best method to predict spring growth initiation. Since soil temperature data are not readily available, an algorithm reported by Moiseichik (1966) is used to convert ambient temperature to soil temperature. The winter wheat phenology model is initiated using actual and/or estimated planting dates. The model resets to 1.4 BMTS growth stage at spring regrowth initiation. Phenological growth stages used in the models are listed in Table 1.

Table 1. Robertson biometerological time scale and phenological growth stages as used in the early warning stress indicator model.

ROBERTSON SCALE	PHENOLOGY STAGE
0.0	Planting
1.0	Emergence
1.5	Tillering
2.0	Jointing
2.5	Flag Leaf
3.0	Heading
3.5	Milk
4.0	Dough
5.0	Ripe

Soil Water Budget Model (Component)

A two-layer soil water budget model developed by Palmer (1965) was modified and implemented by Taylor and Ravet (1981) to provide available soil water estimates needed for the stress function routine. The model assumes that the surface layer holds 2.5 cm of available water and that all additional available water resides in the subsurface layer.

The original Palmer model assumed that water was removed from the surface layer at a rate equal to potential evapotranspiration as calculated by the Thornthwaite method (1948) and that water was removed from the subsurface layer at a fraction of the potential

rate. He also assumed that water could not be removed from the subsurface layer until the top layer was completely dry.

The Palmer model was modified to allow a more gradual and realistic water depletion from the surface layer and to run using daily inputs. The modification also allows for water to be depleted from the subsurface layer before the surface is completely dry. A water extraction function was developed to allow depletion from the surface at the potential ET rate until 75% of the surface capacity is depleted. Below 75%, water is extracted from the surface at a reduced rate with subsurface depletion making up the remaining requirement. Water is extracted from the subsurface layer at a fraction of potential evapotranspiration.

Precipitation enters the model by first completely filling the surface layer and then the subsurface layer. When the available water holding capacity of both layers is reached, excess precipitation is treated as runoff and lost from the model. Input requirements include maximum and minimum temperature, precipitation, and estimated available water holding capacity of the major soils in the region of interest. The following formulation describes the modified soil water budget model:

Surface Layer = Contains 2.5 cm of plant available water.

Subsurface Layer = Normally contains between 12 and 25 cm of available water.

$$L_s = S'_s - (PET-P)\ D_f$$

$$L_u = (PET-P-L_s)\ \frac{S'_u}{AWC} : L_u \leq S_u$$

D_f = Surface water extraction function.

$= 1$ if $P = PET$

$= (S'_s \quad .75) : .1 \leq 1.$

$= .1$ if $D_f < .1$ and $D_f = 1. : D_f > 1.$

R = Excess P after both layers are filled.

$PET = PET'(d)$ [Thornthwaite, 48]

$PET' = 0$, if $T < 0°C$

$= 1.6\ (10T/I)^a$, if $0°C < T < 26°C$

$= \sin\ (T - 9.5) - .76$, if $T > 26°C$

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + .01792I + 49239$$

$$I = \sum_{i=1}^{12} (T/5)^{1.514}$$

$$d = -0.767 \tan\{.41 \operatorname{Cos}[.017(DOY-172)]\}$$

Where

L_s = Water loss from surface

S'_s = Available water in surface layer at start

PET = Potential evapotranspiration

P = Daily precipitation

L_u = Loss from lower layer

S'_u = Available water stored in lower layer

AWC = Combined available water capacity; i.e., $MAX(S'_s + S'_u)$

R = Runoff

D_f = Surface water extraction function

PET' = Unadjusted potential evapotranspiration

d = Day length adjustment for PET

T = Average daily temp degree C

I = Annual heat index

DOY = Day-of-year

a = coefficient

The Stress Function Routine

The degree of stress is dependent on three variables: 1) phenological growth stage, 2) soil water availability, and 3) temperature extremes. Stress was defined in this model version as those factors considered to most affect the wheat growth cycle and for which input data are readily available on a global basis. The model deals only with conditions related to meteorological factors. During each growth stage both optimum and stressed conditions may exist. Optimal and stress conditions that form the model logic are presented by growth stage in Table 2.

Table 2. Stress and optimal conditions, by growth stage, that form the wheat stress model logic.

GROWTH STAGE	STRESS CONDITION	OPTIMUM CONDITION
0.0 - 1.0	Tmin < 3°C	Tmin > 25°C
		Tmax < 30°C
	AWC < 20%,	AWC > 60%,
1.0 - 1.2	Tmin < -7°C	Tmin > 14°C
		Tmax < 22°C, > 14°C
	AWC < 40% surface	AWC > 25%
1.2 - 2.0	Tmin < -7°C	Tmin > 14°C
		Tmax < 22°C, > 14°C
	AWC < 25%, > 95%	AWC > 60%, < 75%
2.0 - 3.0	Tmin < -7°C	Tmin > 14°C
		Tmax < 22°C, > 14°C
	AWC < 40%, > 95%	AWC > 60%, < 75%
3.0 - 3.6	Tmin < 0°C	Tmin > 14°C
	Tmax > 42°C	Tmax < 22°C
	AWC < 40%, > 95%	AWC > 60%, < 75%
3.6 - 4.0	Tmin < 0°C	Tmin > 14°C
	Tmax > 42°C	Tmax < 22°C
	AWC < 25%	AWC > 45%, < 75%
4.0 - 4.5	Tmin < -7°C	Tmin > 14°C
		Tmax < 22°C
	AWC < 12%, > 80%	AWC > 40%, < 60%

*AWC = Available water capacity.

Tractability alerts are provided from 10 days before planting to 10 days after planting and from stage 4.5 to 10 days after maturity. An alert is indicated when the surface layer exceeds 22 mm or when more than 25 mm of precipitation occurs in a given day.

All stress indicator models (wheat, maize, sorghum, sugar beets and soybeans) have the three central components: 1) a crop calendar model, 2) a soil water budget model, and 3) a hazard model. All models require daily maximum and minimum temperature and precipitation.

WHEAT YIELD REDUCTION MODEL

A spring and winter wheat yield reduction model was developed for large-area crop condition assessments. Reductions are expressed in percentage from a base yield and are calculated on a daily basis. The algorithm contains two integral components, the soil water budget and the crop calendar model, both developed for the wheat stress indicator model. There are two distinct modules in the wheat yield reduction model: 1) a Sukhovey/ETP module and 2) a water stress module.

Sukhovey/ETP Module

This module assigns empirically derived yield losses, based on ETP and maximum temperature (Table 3). Additional adjustments are then computed for available soil water (Table 4), modifications based on crop phenology (Figure 1), and Sukhovey duration (Table 5).

Yield reductions may be expressed by

$$YR = ETP/MTF * SWAF * SDF * CPF$$

where:

YR = Yield Reduction
ETP/MTF = Evapotranspiration Potential/Maximum Temperature Factor
SWAF = Soil Water Availability Factor
SDF = Sukhovey Duration Factor
CPF = Crop Phenology Factor

The crop phenology factor, prior to stage 4, is computed by

$$CPF = 8.208-9.452X+3.405^2-0.3666X^3$$

The crop phenology factor, stage 4 to maturity, is computed by

$$CPF = 16.94-6.829X+0.948X^2-0.52X^3$$

Where X = crop phenology

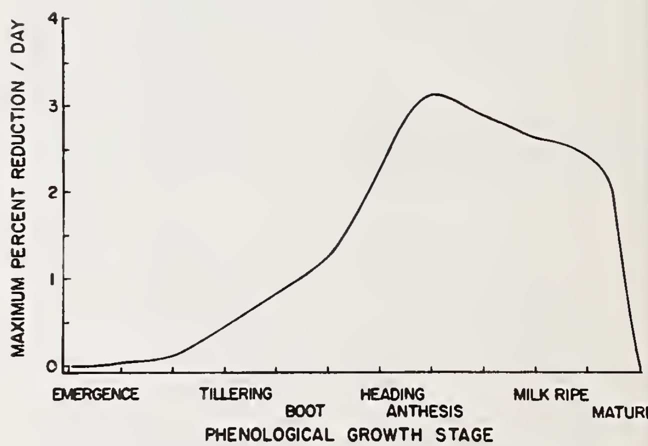

Figure 1. Daily wheat yield reduction potential.

Water Stress Module

If the Sukhovey/ETP module criteria are not met, the algorithm then defaults to the water stress module. The stress

Table 3. Wheat Yield Reduction Factors Associated with Evapotranspiration (mm/Day) and Maximum Temperature, (°C).

		E V A P O T R A N S P I R A T I O N P O T E N T I A L												
		8	9	10	11	12	13	14	15	16	17	18	19	20
		Mm/Day												
M	26	0	0	0	0	0	0	0	0	0	1	2	3	4
A	27	0	0	0	0	0	0	0	1	2	3	4	5	6
X	28	0	0	0	0	0	1	2	3	4	5	6	7	8
I	29	0	0	0	1	2	3	4	5	6	7	8	9	10
M	30	0	1	2	3	4	5	6	7	8	9	10	11	12
U	31	2	3	4	5	6	7	8	9	10	11	12	13	14
M	32	4	5	6	7	8	9	10	11	12	13	14	15	16
	33	6	7	8	9	10	11	12	13	14	15	16	17	18
T	34	8	9	10	11	12	13	14	15	16	17	18	19	20
E	35	10	11	12	13	14	15	16	17	18	19	20	21	22
M	36	12	13	14	15	16	17	18	19	20	21	22	23	24
P	37	14	15	16	17	18	19	20	21	22	23	24	25	26
E	38	16	17	18	19	20	21	22	23	24	25	26	27	28
R	39	18	19	20	21	22	23	24	25	26	27	28	29	30
A	40	20	21	22	23	24	25	26	27	28	29	30	31	32
T	41	22	23	14	25	26	27	28	29	30	31	32	33	34
U	42	24	25	26	27	28	29	30	31	32	33	34	35	36
R	43	26	27	28	29	30	31	32	33	34	35	36	37	38
E	44	28	29	30	31	32	33	34	35	36	37	38	39	40
C	45	30	31	32	33	34	35	36	37	38	39	40	41	42

Table 4. Wheat Yield Reduction Factors Associated With Soil Water Availability; Modified by Growth Stage Factors in Figure 1.

%AWC	YIELD REDUCTION FACTOR
5	1.25
10	1.25
15	1.25
20	1.20
25	1.15
30	1.10
35	1.05
40	1.00
45	0.99
50	0.98
55	0.97
60	0.96
65	0.95
70	0.94
75	0.93
80	0.92
85	0.91
90	0.90
95	0.89
100	0.88

Table 5. Wheat Yield Reduction Factors Associated With Consecutive Days of Sukhovey Conditions.

DAY	ADJUSTMENT
1	1.0
2	0.5
3	0.25
4	0.125
5	0.0625
6	0.03125

module assesses yield reduction using ETP, available soil water and crop phenology. The model assumes ETP to be the sum of the demands that are placed on the plant by the environment. Evapotranspiration potential demands are then used to calculate a stress index. The stress index is a regression equation expressed in terms of water and ETP. The Stress index is computed by

$$\text{Stress Index} = .9998 + (.108\ \text{ETP}) + (.0145\ \text{AWC}) - (.3536\ (\text{AWC})^{.5})$$

where:

Stress Index = crop stress index between 0 and 1
ETP = evapotranspiration potential
AWC = percent of soil water available to plants

SUMMARY

The early warning stress indicator model and the yield reduction model for wheat have been transferred to USDA-FAS and are currently in use by their Foreign Crop Condition Assessment Division. Based on two years of operational testing by the FAS, the models provide useful information to their crop analyst. In addition to the yield reduction and wheat stress indicator models, early warning stress indicator models have been developed for maize, sorghum, sugarbeets, soybeans and for wheat winterkill problems.

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CHAPTER 13. SENSITIVITY ANALYSIS OF WHEAT MODELS

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INTRODUCTION

The Statistical Reporting Service (SRS), U. S. Department of Agriculture is investigating the use of plant simulation models to forecast large-area wheat yields. Present SRS forecasting methods perform very well after the crop has begun producing fruit that can be destructively sampled. However, for earlier plant growth stages, the methodology depends on historic averages and regression relationships that are not very responsive to the current season environmental characteristics which largely determine the final grain yield. Improved early-season yield forecasts are needed, particularly in atypical years, for decision makers in Government, agribusiness, and farm management.

SRS is evaluating several wheat models for large-area yield forecasting use. Once initial validation has been conducted on a plot level to demonstrate adequate ability to estimate plant phenology and yield, sensitivity analysis is performed. Such analysis assesses the relative sensitivity of model response to variations in data inputs and internal model parameters and functions. In this context, sensitivity information serves two main purposes. The first is to help determine the accuracy and resolution required for model inputs in a large-area application. Second, identification of the most influential parameters and functions in the model tells the model developer where to concentrate efforts to improve the accuracy of the simulation.

In SRS, the term "large-area application" primarily refers to state-level yield forecasts. Putting the forecasting issue aside for the moment, there are two basic ways to obtain state-level yield estimates from a wheat model which has been validated at the plot level -- aggregate the model inputs to the state level and run the model once, or run the model on individual data sets from a representative number of plots and aggregate the model outputs. Some combination of the two methods can also be used. For example, model inputs can be aggregated to the crop reporting district (CRD) level and CRD-level model yields can be aggregated to the state level. In the case of models composed of many nonlinear relationships, aggregation of model inputs should be avoided because there is no guarantee that the model yield obtained from aggregated plot data will equal the average of the model yields obtained from separate runs on the individual plots. Highly aggregated inputs would probably provide comparable results under "normal" growing conditions but it is the unusual seasons and extreme responses that are of the most interest to SRS.

Therefore, the currently proposed SRS large-area application procedure is to run the model for individual plots and aggregate the model yields to the state level. This approach fits in with the format of the operational objective yield survey which simplifies data collection. Because it is not economically feasible to accurately estimate all model inputs at the plot level, sensitivity analysis is used to determine the conditions when certain inputs can be estimated less accurately with-

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out adversely affecting the model yield. For example, it is clear that initial soil water estimates can be very rough with certain combinations of initial soil water and total seasonal rainfall.

Since SRS is mainly interested in improving early-season forecasts rather than end-of-season estimates, something must be done to handle future weather conditions must be accounted for in some manner. Two approaches are presently being considered for large-area application. One is to simulate possible sequences of daily climatic data and substitute these in place of the unknown model inputs. A different sequence should be used for each plot-level model yield forecast. This method accommodates the use of any available (and dependable) long-range weather forecasts and permits probability statements concerning the state-level yield forecast.

A second approach to forecasting is to replace the daily model values of certain yield-related variables with time-series representations. One possibility is to obtain a nonlinear time-series description of the simulated total plant biomass up to the forecast date and then project an end-of-season biomass estimate from the fitted function. A regression relationship could then be used to obtain a yield forecast from the biomass. Model variables other than biomass or additional model variables could be used. A time-series approach to forecasting would not need simulated daily climatic data since the plant model would not run past the forecast date.

This paper discusses the sensitivity analysis methods that have been used since SRS became actively involved in the ARS Wheat Yield Project and summarizes the results for the November 1982 version of the CERES-wheat model by J. T. Ritchie, et al. In addition to the November 1982 CERES-wheat model, extensive sensitivity analysis has been done on an earlier 1980 version and on the Texas A&M Wheat (TAMW) model by S. F. Maas and G. F. Arkin (8). Use of the Kansas State University wheat model by E. T. Kanemasu for large-area yield forecasting was investigated via a cooperative agreement (2).

SENSITIVITY ANALYSIS METHODS

There are many ways to investigate the sensitivity of model response to changes in the levels of selected factors. Perhaps the simplest approach is to perturb the factors individually and observe the model response. The sensitivity can be quantified by finding the value when relative change in response divided by relative change in the factor is a maximum. This amounts to finding the steepest slope on a response curve composed of several line segments connecting individual response points. One problem with this method is that the observed maximum slope is dependent on the frequency and spacing of the response points and will always be less than the maximum slope on the true response curve. Thus, in general, a better estimate of the true maximum slope can be obtained by observing the response at a larger number of points.

Another consideration in using this method is that all the response points are not equally likely to occur. For example, if the model yield response is being investigated for sensitivity to changes in initial soil water, the maximum slope occurs for relatively low soil water values. However, it may be that such low initial soil water conditions are very unlikely at specific locations. This consideration suggests that probability of occurrence might be

combined with the slope to provide a sensitivity measure which is more comparable among different factors at specific locations. In this procedure a compromise must be made on the number of response points used to alleviate the dependence of the observed maximum slope on frequency and spacing because the probability of occurrence of responses between successive points approaches zero as the number of points increases. Also, each response point is obtained by running the model with the factor of interest at a desired level. Increasing the number of response points adds to the cost of the analysis. The so-called maximum slope and probability sensitivity measures were used to quantify the sensitivity of model yield and phenology to changes in the required inputs and several fixed parameters and functions in the 1980 version of the Ritchie wheat model and the TAMW model. This work was discussed in a 1981 progress report (3).

There are at least two major drawbacks to the methods discussed thus far. The first is that many of the factors are interrelated and perturbation of factors individually does not allow estimation of possible interactions. Secondly, a large number of model runs is needed to adequately estimate the individual response curves when there are many potentially influential factors. Baker and Bargmann (1) suggested that response surface techniques be used to alleviate these problems. The basic idea is to approximate the model response within a specified range of factor perturbation with a fitted surface. The factors are the model inputs, parameters or functions of interest in the sensitivity analysis. The fitted surface is used to estimate factor effects, interactions, and sensitivity measures which can be compared among factors.

Response surface methods were used to analyze the required inputs for the CERES-wheat and TAMW models. The response surfaces were second-order so that linear, quadratic, and interaction effects could be estimated. Response points were obtained according to an orthogonal central composite design. A central composite design for k factors is composed of a 2^k factorial with 2k "axial" points and a "center" point added. The center point is the model response when none of the factors are perturbed. The axial points are obtained by perturbing each factor individually by a specified amount relative to the factorial points. This amount is selected so that the design is orthogonal. That is, the estimated factor effects are independent of one another and have minimum variance. The factor perturbation ranges were chosen so that they were reasonable and, also consistent among factors unless there was good evidence to do otherwise. Two sensitivity measures were computed with the fitted response surfaces. One is mentioned here and is called the relative sensitivity measure. It is computed by dividing each estimated factor effect by the model response at the center point. This method gives a proportion which indicates the relative influence of each factor. Details of the response surface analysis are contained in two 1983 reports (5, 6).

Response surface methods are convenient when the number of factors of interest is small, say, six or less. Beyond that the number of model runs needed to obtain the response points becomes prohibitively large. This restriction is not as severe as it appears because often a larger set of factors can be subsetted and separate response surface experiments run. The most influential factors from each experiment can be placed in a combined experiment to

better assess overall sensitivity. This procedure precludes the estimation of all possible interaction effects among the original set of factors but, with prudent subsetting, the number of statistically significant interactions that are missed can be minimized.

The sensitivity analysis was done for model inputs and fixed parameters and functions. The response surface methods were convenient for the inputs but not directly applicable to the parameters and functions because the number of potentially influential factors is large. Thus, a screening procedure was used to effectively reduce the number of factors to be included in the response surface experiments for parameters and functions. This screening was done in two ways -- path coefficient analysis and multistage group screening. Path coefficient analysis was used to identify the most critical model variables and subroutines in TAMW. The basic procedure is to identify the causal relationships of all the unique model variables by studying the computer source code. The causal ordering of the variables is then shown in a path diagram. The causal ordering identifies particular structural equations containing path coefficients. The coefficients can usually be estimated with ordinary least squares regression. The estimated path coefficients are then combined to obtain direct and indirect effects of the model variables on the model response of interest. Once the most influential variables and associated subroutines are found, the size of the model is effectively reduced. Parameters and functions from the reduced model can be selected for sensitivity analysis using response surface methods. The application of path coefficient analysis to TAMW is discussed in a 1983 report (4).

The path analysis provided the desired information but proved to be quite complex and time consuming. Multistage group screening was used in the analysis of the CERES-wheat parameters and functions. The first step in this screening procedure is to identify all the factors to be considered. Ideally one wants to include all the parameters and functions that have any possible effect on the model response of interest. The basic procedure, then, is to separate the factors into groups. An appropriate experimental design is used to test the statistical significance of the group effects on model response. This design treats each group as an individual factor. Consequently, the effects of individual factors within groups are inseparable. After the significant groups are found in the first stage, the remaining factors are re-grouped into smaller group sizes(i.e. fewer factors within each group) and another experimental design is employed to identify significant groups in the second stage. The process continues until the group size reaches one. Finally, the individual factors are tested and one hopes that the significant factors in the last stage are the same as those which would have been obtained had each factor been tested individually at the start.

The advantage of group screening is that with a large number of factors, the most important can be found with considerably fewer model runs than necessary without grouping. There is some risk that the procedure will miss an important factor, and there are a number of considerations necessary to minimize this risk. The experimental designs used at each stage of the procedure allow for estimates of the main effects free of confounding with each other or with two-factor interactions. But, estimates cannot be made for individual two-factor interactions or quadratic effects.

Once the most important factors have been obtained from the procedure, the aforementioned response surface methods can be used to quantify the sensitivity in more detail if desired. When screening the parameters and functions in a model, the purpose is to identify the most influential so that the model developer can make sure his estimates are as accurate as practical. Simply identifying the important factors with a linear model is probably sufficient so that response surface analysis may be unnecessary. Details of the group screening procedure and results are contained in a 1983 report (6).

RESULTS AND DISCUSSION

This section summarizes the results of the sensitivity analysis on the November 1982 version of the CERES-wheat model. The analysis was done in two main parts. The first part examined the sensitivity of model response to changes in the required model inputs. The second part of the analysis identified the most critical parameters and functions in the model.

Five main response surface experiments were run on the CERES data inputs. The model responses of main interest were grain number, weight per grain, tiller number, and grain yield. The input data for all the experiments were based on Manhattan, Kansas conditions. The initial inputs used are typical for the Manhattan area and include an October 1 planting date, 20 cm row spacing, density of 189 plants per square meter, sowing depth of 4 cm, and 60% initial plant available soil water. Several parameters were also specified for soils common to the Manhattan area. Genetic specific parameters for Scout 66 winter wheat were taken from a file supplied with the model. Daily climatic inputs for the CERES-wheat model were simulated using a stochastic weather simulation model (7). Several random sequences were generated and three were selected to give a range in growing conditions. Summary statistics for the climatic data are given in Table 1. The climatic scenarios (called "blocks" in the analysis) are ordered from the wettest season to the driest. As a basis of comparison, Table 1 also gives summary statistics

Table 1 - Summary data for three simulated seasons of climatic data at Manhattan, Kansas.

Block	Days per Season	Total Rainfall (cm)	Avg. Max. Temperature (°C)	Avg. Min. Temperature (°C)	Avg. Daily Solar Radiation (Ly)
1	259	76.50	13.7	1.4	317.5
2	257	47.09	13.4	1.6	325.7
3	257	38.43	13.8	1.4	327.2
Actual1/	257	47.2 (10.4)	14.2 (.64)	1.7 (.57)	312.1 (10.8)
	259	48.0 (10.4)	14.3 (.64)	1.8 (.58)	314.0 (10.8)

1/ Based on 22 years of observed data. The standard errors are in parentheses.

for 22 years of observed data at Manhattan using the same lengths of growing season as in the simulated data.

The planting date, plant density and sowing depth were not influential in determining the model yield in this analysis. The planting date could become more of a factor in specific growing seasons in which there is large day-to-day variation in the climatic inputs around the time of planting. The plant density would become more important for low seeding rates, say fewer than 100 plants per m^2. However, good plot-level estimates of plant density should be readily obtainable in a large-area application. The sowing depth would influence the yield more if planting conditions are extremely dry. However, good plant density estimates would account for the effect of poor germination.

Eight soil water parameters were tested for their effect on model yield. In this part of the analysis, the initial actual soil water content (SW) was fixed. Accurate estimates of these parameters are not needed unless the total seasonal rainfall is 40-43 cm or less. The average total rainfall in Manhattan, Kansas for a 257-day growing season is 47.2 cm. The lower limit (LL), drained upper limit (DUL), and saturated soil water content (SAT) were considered jointly in this analysis because they are highly correlated and, hence, it would be unrealistic to perturb them independently. When total rainfall is less than 40-43 cm, LL, DUL and SAT are the most influential of the eight parameters. With 38 cm of sea sonal rainfall, a 10% error in LL, DUL, and SAT converts to roughly a 6.4% change in the model yield. The model sensitivity to errors in these three parameters would likely increase with even drier growing conditions. In a large-area application, LL is of the most concern because it determines the amount of available water to the simulated plant. Thus, even if SW is known at planting and the model exactly simulates the change in soil water during the season, a 10% error in LL will change the final model yield by 6.4% or more when the seasonal rainfall is approximately 38 cm or less. LL is not a particularly easy parameter to estimate in a large-area application.

Eight genetic specific parameters were considered in the sensitivity analysis. The control variety was Scout 66 which is prevalent in Kansas. Two parameters which help determine the grain number and grain filling rate had the greatest influence on yield. In a large-area application, the values of the genetic parameters are obtained from a file supplied with the model. Thus the model developer is responsible for parameter estimation and the user need only specify the variety. Accurate estimates of the two most important parameters are needed because a 10% error in either means approximately a 10% change in yield.

The last initial input variable tested was the actual soil water content expressed in terms of the percentage available to the plant (i.e. (SW-LL)/(DUL-LL)). In this part of the analysis LL and DUL were fixed. The plant available soil water was combined in several experiments with the required daily inputs -- precipitation, maximum and minimum temperature, and solar radiation. The effect of starting the soil water balance up to three months before planting was also examined. Initial soil water and daily precipitation had the largest influence on yield in all experiments except the one in which the seasonal rainfall was far above average (i.e. block 1 in Table 1). The results showed that if

the total seasonal rainfall exceeds 47 cm and the initial plant available soil water is at least 60% then these two water-related variables have small effects on model yield. With 38 cm of rainfall and 60% initial soil water as the base level, a decrease of 10% in the initial soil water causes a decrease of 8.8% in the yield. A decrease of 10% in the rainfall lowers the yield 7.7%. When the soil water balance is started three months before planting, 10% decreases in either initial soil water or daily rainfall cause 2.8% and 6.6% decreases in the yield, respectively. Thus, starting the soil water balance three months earlier reduced the sensitivity of the yield response to changes in initial soil water considerably. Many growing seasons in major wheat producing regions have less than 38 cm of rainfall. Therefore, in a large-area application it may be necessary to have accurate soil water and precipitation estimates when seasonal rainfall is below 38 cm.

It is difficult to generalize the temperature effect. There appeared to be a tendency for the temperature effect to increase as the seasonal rainfall decreased. The largest effect observed was in the driest season when the soil water balance began at planting. In this case a 1°C increase in temperature caused a 13.3% decrease in yield. For large-area application, random errors of 2-4 C can probably be tolerated at the plot level but systematic errors (bias) must be very small. Solar radiation effects were small in this analysis but other sets of daily climatic data might show different results. To be safe bias in the solar radiation estimates should be small but fairly large random errors probably would not change the model yield much.

A total of 131 parameters and functions in the CERES-wheat model were identified for analysis with multistage group screening. It was decided that approximately 10% of these would be identified as being the most influential in determining the model yield and components. The same four response variables as in the response surface experiments were used -- grain number, weight per grain tiller number, and grain yield. The driest season of simulated daily climatic data at Manhattan, Kansas (block 3 in Table 1) was used as model input. Of the 131 factors initially included in the analysis, 14 were singled out as being the most influential in determining at least one of the four model responses. The results were reviewed by the model developer and this part of the analysis did provide useful information for possible model improvement. More detailed results of the sensitivity analysis on the CERES-wheat model can be obtained in the report (6).

SUMMARY AND CONCLUSIONS

Sensitivity analysis has been done on two wheat models. The results gave model developers a better idea of where continued model refinement would provide the largest potential gains in simulation accuracy. The analysis also gave some guidelines for required input accuracy in a large-area application. SRS has begun planning a research study that would provide the data to assess which input estimation methods would provide satisfactory results. If this study provides a feasible means of obtaining the required model inputs on a large scale then operational testing of the wheat models for large-area yield forecasting would follow. At the present time, there is reason to

believe that plant models will be able to provide improved early-season yield forecasts in the SRS operational program.

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245

CHAPTER 14. A SUMMARY OF VEGETATION INDICES DEVELOPED FOR REMOTE SENSING //

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INTRODUCTION

The aim of science is to seek the simplest explanation of complex facts. We are apt to fall into the error of thinking that the facts are simple because simplicity is the goal of our quest. The guiding motto in the life of every natural philosopher should be, "Seek simplicity and distrust it."
Alfred North Whitehead

Current and accurate information on global basis regarding the extent and condition of the world's major food and fiber crops is important in today's complex world. Traditional sampling techniques for estimating crop conditions, based on field collection of data, are time consuming, costly, and not generally applicable to foreign regions. An alternate approach is remote sensing. A series of earth observation satellites (Landsats) have provided a potential way to monitor worldwide crop conditions [McDonald and Hall (1980)]. The sensor system onboard the Landsats, the multispectral scanner (MSS), measures the reflectance of the scene in four wavelength intervals (channels) in the visible and near-infrared portions of the spectrum. The spectral measurements are influenced by the vegetation characteristics, soil background, and atmospheric condition.

Investigators have developed techniques for qualitatively and quantitatively assessing the vegetative canopy from spectral measurements. The objective has been to reduce the four channels of MSS data to a single number for predicting or assessing such canopy characteristics as leaf area, biomass, and percent ground cover.

This paper summarizes and references the origin, derivation, and motivation for some four dozen of these formulae which are referred to as vegetation indices (VIs). Part II develops the idea of two VIs being functionally equivalent for decision making. The meaning and utility of VIs equivalence is demonstrated in a sequence of real and hypothetical examples.

A HISTORICAL SUMMARY OF VEGETATION INDICES

Idealized reflectance patterns for herbaceous vegetation and soil are compared in Figure 1. Dead or dormant vegetation has higher reflectance than living vegetation in the visible spectrum and lower reflectance in the near-infrared. Soil has higher reflectance than green vegetation and lower reflectance than dead vegetation in the visible, whereas in the near-infrared, soil typically has lower reflectance than green and dead vegetation [Tappan (1980)]. Jackson et al. (1980), Tucker and Miller (1977), and Deering et al. (1975) provide an extensive discussion of reflectance properties.

Numerous vegetation indices have been used to make quantitative estimates of leaf area index, percent ground cover, plant height, biomass, plant population, and other parameters [Pearson and Miller (1972) and Wiegand et al. (1974)]. Most formulae are based on ratios or linear combinations and exploit differences in the reflectance patterns of green vegetation and other objects as summarized in Figure 1.

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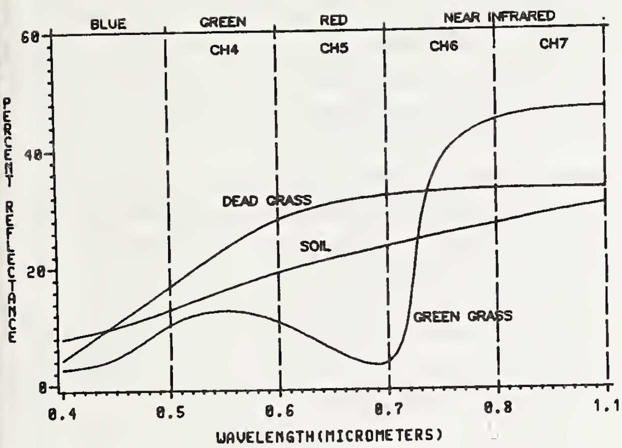

Figure 1. Idealized reflectance patterns of herbaceous vegetation and soil from 0.4 to 1.1. Micrometers [Deering (1975)].

The digital counts (DCs) from the individual MSS channels (CH4, CH5, CH6, CH7) have been used to estimate percent ground cover and vegetative biomass [Wiegand et al. (1974) and Seevers et al. (1973)]. The correlation coefficients reported ranged from 0.30 for CH7 with crop cover to 0.88 for CH6 with leaf area index. Similar correlations were reported by Tucker (1979).

Ratios of the MSS DCs have been used to estimate and monitor green biomass, etc. [Rouse et al. (1973, 1974), Carneggie et al. (1974), Johnson (1976), and Maxwell (1976)]. The coefficients of determinations were slightly higher than those for the corresponding channel differences. The twelve pairwise ratios (six of which are inverses of the other six) will be denoted by R45 = CH4/CH5, R46 = CH4/CH6, etc.

Rouse et al. (1973) proposed using the normalized difference of DCs from CH7 and CH5 for monitoring vegetation, which will be referred to as ND7.

Deering et al. (1975) added 0.5 to ND7 to avoid negative values and took the square root of the result to stabilize the variance. This index is referred to as the transformed vegetation index and will be denoted by TVI7. Similar formulae using CH6 and CH5 were proposed:

$$\begin{aligned} ND6 &= (CH6 - CH5)/(CH6 + CH5) \\ ND7 &= (CH7 - CH5)/(CH7 + CH5) \\ TVI6 &= (ND6 + 0.5)^{1/2} \\ TVI7 &= (ND7 + 0.5)^{1/2} \end{aligned}$$

Our experience has been that the addition of 0.5 does not eliminate all negative values. We suggest the following computationally correct formulae:

$$TVI6 = \frac{(ND6 + 5)}{ABS(ND6 + .5)[ABS(ND6 + .5)]^{1/2}}$$

$$TVI7 = \frac{(ND7 + .5)}{ABS(ND7 + .5)[ABS(ND7 + .5)]^{1/2}}$$

where ABS denotes absolute value, and 0/0 is set equal 1. In Example 1, (given later), it is shown that these formulae are equivalent for decision making to the basic ratios R65 and R75. Therefore, their use can only be justified if either they improve the regression fit or they normalize the regression errors [Draper and Smith (1966)].

Kauth and Thomas (1976) used the technique of sequential orthogonalization underlying the Gram-Schmidt process to produce an orthogonal transformation of the original Landsat data space to a new four-dimensional space. They called it the "tasseled cap" transformation and named the four new axes brightness (soil brightness index, SBI), greenness (green vegetative Index, GVI), yellow stuff (YVI), and non-such (NSI). The names attached to the new axes indicate the characteristics the indices were intended to meas-

ure. The coefficients in the following formulae are taken from Kauth et al. (1978).

$$SBI = .332\ CH4 + .603\ CH5 + .675\ CH6 + .262\ CH7$$
$$GVI = -.283\ CH4 - .660\ CH5 + .577\ CH6 + .388\ CH7$$
$$YVI = -.899\ CH4 + .428\ CH5 + .076\ CH6 - .041\ CH7$$
$$NSI = -.016\ CH4 + .131\ CH5 - .452\ CH6 + .882\ CH7$$

Wheeler et al. (1976) and Misra et al. (1977) applied principal component analysis to MSS DC data. The structure of the resulting transformation and the interpretation of the principal components are similar to those for the Kauth-Thomas transformation.

$$MSBI = .406\ CH4 + .600\ CH5 + .645\ CH6 + .243\ CH7$$
$$MGVI = -.386\ CH4 - .530\ CH5 + .535\ CH6 + .532\ CH7$$
$$MYVI = .723\ CH4 - .597\ CH5 + .206\ CH6 - .278\ CH7$$
$$MNSI = .404\ CH4 - .039\ CH5 - .505\ CH6 + .762\ CH7$$

The similarity of the Kauth-Thomas and Wheeler-Misra results is remarkable in light of the fact that the ideas and techniques underlying the two processes are quite different. With principal component analysis the experimenter imposes no prior order or physical interpretation on the principal directions. Principal component analysis is in effect a successive factorization of the total variation in the data into mutually orthogonal components, the order being established by the successive directions of maximum variation. Gram-Schmidt orthogonalization, however, gives the experimenter the freedom to indirectly establish a physical interpretation by choosing the order in which the calculations are performed.

Misra et al. (1977) proposed another linear transform, based on the idea of spectral brightness and contrast. Generalizations of spectral brightness and contrast were defined in spectral density space, then transformed back to count space. The first two components of the resulting transformation are similar to the first two components of the two preceding transformations.

$$SSBI = .437\ CH4 + .564\ CH5 + .661\ CH6 + .233\ CH7$$
$$SGVI = -.437\ CH4 - .564\ CH5 + .661\ CH6 +.233\ CH7$$
$$SYVI = -.437\ CH4 + .564\ CH5 - .661\ CH6 + .233\ CH7$$
$$SNSI = -.437\ CH4 + .564\ CH5 + .661\ CH6 - .233\ CH7$$

Richardson and Wiegand (1977) used the perpendicular distance to the "soil line" as an indicator of plant development. The "soil line", a two-dimensional analogue of the Kauth-Thomas SBI, was estimated by linear regression. Two perpendicular vegetation indices were proposed.

$$PVI7 = [(.355\ CH7 - .149\ CH5)^2 + (.355\ CH5 - .852\ CH7)^2]^{1/2}$$
$$PVI6 = [(-.498 - .457\ CH5 + .498\ CH6)^2 + 2.734 + .498\ CH5 - .543\ CH6)^2]^{1/2}$$

Evidently a minor error was made in the derivation of PVI6. The formula for PVI6 should be:

$$PVI6 = [(-2.507 - .457\ CH5 + .498\ CH6)^2 + (2.734 + .498\ CH5 - .543\ CH6)^2]^{1/2}$$

These formulae are computationally inefficient and do not distinguish right from left of the soil line (water from green stuff). The standard formula from analytic geometry for the perpendicular distance from a point to

a line solves this difficulty [Salas and Hille (1978)].

$$PVI6 = \frac{(1.091\ CH6 - CH5 - 5.49)}{(1.092^2 + 1^2)^{1/2}}$$

$$PVI7 = \frac{(2.4\ CH7 - CH5 - .01)}{(2.4^2 + 1^2)^{1/2}}$$

The difference vegetation index (DVI), suggested by Richardson and Wiegand (1977) as computationally easier than PVI7, is essentially a rescaling of PVI7.

$$DVI = 2.4\ CH7 - CH5$$

The Ashburn vegetation index [Ashburn (1979)] was suggested as a measure of green growing vegetation. The doubling of CH7 is to make the scale compatible; CH7 is 6-bit data and has one-half the range of the other three bands which are 8-bit data.

$$AVI = 2.0\ CH7 - CH5$$

Hay et al. (1979) proposed a vegetation indicator called greenness above bare soil (GRABS). This was an attempt to develop an indicator for which a threshold value could be specified for detecting green vegetation. The calculations were made using the Kauth-Thomas tassel cap transformation applied to sun-angle and haze-corrected data. The resulting index is quite similar to the GVI, since the contribution of SBI is less than 10 percent of GVI.

$$GRABS = GVI - .09178\ SBI + 5.58959$$

Kanemasu et al. (1977) regressed winter wheat leaf area measurements on MSS band ratios and produced the following regression equation.

$$\begin{aligned} ELAI = {} & 2.68 - 3.69\ R45 - 2.31\ R46 \\ & + 2.88\ R47 + 0.43\ R56 \\ & - 1.35\ R57 + 3.07\ [R45 \\ & - (.5\ R45\ (R45)] \end{aligned}$$

Pollack and Kanemasu (1979) later used a larger data set plus stepwise regression and obtained another regression equation.

$$\begin{aligned} CLAI = {} & .366 - 2.265\ R46 - .431(R45 \\ & - R47)(R45) + 1.745\ R45 \\ & + .057\ PVI7 \end{aligned}$$

Separate regression equations were also obtained for CLAI values above and below 0.5.

$LAI = 1.903 - 1.138\ R56 - .071(R45 - R47)R45 - .016\ PVI6$, if CLAI is less than 0.5

$LAI = -5.33 + .036\ PVI7 + 6.54\ TVI6$, if CLAI is greater than 0.5

Thompson and Wehmanen (1979) proposed a technique utilizing transformed DC data for detection of agricultural vegetation undergoing water stress. The MSS data are rotated into the Kauth-Thomas vectors (GVI, SBI, YSI, NSI) to screen out clouds, water, bare soil, etc. Each vector is evaluated and any vector having values considered unreasonable for agricultural data is discarded. The remaining pixels are considered the good pixels. One percent of the pixels with the lowest GVI values are then discarded. The lowest GVI value remaining becomes the soil line. A green number is then computed for each pixel by subtracting the soil line from GVI. The Green Index Number (GIN) is then an estimate of the percentage of pixels in the scene with a green number greater than or equal to 15, or

$$GIN = \frac{\text{pixels with green number}}{\text{good pixels}} * 100$$

SOME EMPIRICAL RELATIONSHIPS AMONG VEGETATIVE INDICES

Richardson and Wiegand (1977) correlated eight VIs (GVI, DVI, SBI, PVI6, PVI7, TVI6, TVI7, and R57) with four plant component variables (crop cover, shadow cover, plant height, and leaf area index). The correlation coefficients obtained by plant component with the VIs (excluding SBI) were very similar. Later, Wiegand et al. (1979) correlated leaf area indices for winter wheat fields to five VIs (TVI7, TVI6, PVI7, PVI6, and GVI). The correlation coefficients within and among fields were similar.

Aaronson et al. (1979) studied the similarities and differences among several VIs (AVI, DVI, GVI, PVI7, TVI7, and KVI). The resulting correlation coefficients ranged from 0.8 to 1.0 and were stable from spring greenup to harvest. Aaronson and Davis (1979) later used a large data set, which included vegetation measurements and several VIs, to study interrelationships. The VIs (AVI, DVI, GVI, KVI, PVI6, PVI7, TVI6, and TVI7) were correlated against each other and against vegetation measures such as wheat plant height from tillering through harvest. The correlation coefficients between the VIs ranged from 0.81 to 1.00, and those between VIs and vegetation measures mostly cluster around 0.7.

Lautenschlager and Perry (1980-81) studied the empirical relationships among the VIs listed in the above section using cluster analysis. The absolute value of the bivariate correlations was used as the measure of distance between VIs, and the average distance between elements was used as the between-cluster distance. This procedure separated the VIs into two large groups plus a number of small groups. One large group contained VIs based on CH5 and CH7, which included AVI, PVI7, R75, TVI7, and ND7. The other large group contained VIs, based on CH5 and CH6, and a few VIs involving three or all four channels, which included GRABS, CLAI, R65, TVI6, ND6, GVI, MGVI, PVI6, and SGVI. The VIs within these two groups had absolute simple linear correlations greater than 0.90, with most greater than 0.95. The elements of these two large groups were correlated at 0.8 or higher. Three smaller groups readily apparent were: (NSI, R76), (R64, R74), and (SBI, MSBI, SSBI, SNSI).

SOME FUNCTIONAL RELATIONSHIPS AMONG VEGETATION INDICES

In this section, a definition of VI equivalence is developed. The utility of this definition is demonstrated by use of examples in the context of alarm models and graphical display. Vegetation indices are functions which associate a real number to each four-dimensional MSS DC vector, (CH4, CH5, CH6, CH7). To give a precise statement of vegetation index equivalence it is convenient to employ standard function notation: $f:S_1 \dashrightarrow S_2$ denotes a function from the set S_1 into the set S_2; f(X), the value of f at the point (X) of S_1; Dom(f), the domain of f; Ran(f), the range of f; and $f^{-1}:S_2 \dashrightarrow S_1$, the inverse of f when it exists. The inverse exists if, and only if, f is one-to-one and onto (see Appendix A). The composition of two functions has an inverse if, and only if, both functions have inverses, in which case $(f \circ g)^{-1} = g^{-1} \circ f^{-1}$. The reader unfamiliar with this notation may wish to study Figures 2 through 4 before proceeding to the formal presentation that follows. A short explanation of the function notation is given in Appendix A.

It might seem that VI equivalence should correspond to function equality; i.e., $V_1 = V_2$ if, and only if, $V_1(X) = V_2(X)$ for each MSS DC vector X. However, this requirement is too restrictive because it requires that both VIs have the same graph and ignores the decisions made on the basis of the VI values. Because vegetation indices are formulae used in making decisions about crop characteristics and conditions, it is appropriate to say that two VIs are equivalent if, and only if, the same decision results regardless of the VI employed. This means that two VIs, V_1 and V_2, are equivalent for making the set of decisions D if, and only if, for every decision rule d_1:Ran(V_1)-->D, there corresponds a decision rule d_2: Ran(V_2)-->D such that the decision, based on d_2 and V_2, is the same as the decision based on d_1 and V_1 for all MSS DC vectors X; that is, $d_1[V_1(X)] = d_2[V_2(X)]$ for each X. It is easy to see that two vegetation indices, V_1 and V_2, are equivalent if, and only if, there exists a one-to-one onto function T:Ran(V_1)--Ran(V_2) such that $T \circ V_1 = V_2$. Thus the same decision results regardless of the VI used; that is

$$V_1^{-1}[T^{-1}(d)]=(T \circ V_1)^{-1}(d) = V_2^{-1}(d) \qquad \text{(Eq 1)}$$

for each decision d in D, where the superscript -1 indicates the inverse image of d under the given function. The relationship defined is an equivalence relation on the set of vegetation indices; that is,

i. Each VI is equivalent to itself: Reflexive property.

ii. If V_1 is equivalent to V_2, then V_2 is equivalent to V_1: Symmetric property.

iii. If V_1 is equivalent to V_2, and V_2 is equivalent to V_3, then V_1 is equivalent to V_3: Transitive property.

Many tedious computations are avoided by using these properties.

A number of studies have investigated the transformed vegetation indices TVI6 and TVI7 and the corresponding ratios R65 and R75 as predictors of biomass, leaf area, plant height, and percent cover. The predictive ability of TVI6 and R65 or TVI7 and R75 are similar as evidenced by the estimated correlation coefficient. We now show that the transformed vegetation index and its generalizations are equivalent to the corresponding ratios. The sequence of examples that follows will make clear not only the algebraic and geometric meanings of VI equivalence but also demonstrate the utility and appropriateness of this definition.

EXAMPLE 1

Let a and b be positive constants, and define the functions f, g, and T by

$$f(X_5,X_7) = (aX_7 - bX_5)/(aX_7+ bX_5)$$

$$g(X_5,X_7) = X_7/X_5$$

$$T(y) = (b/a)[(1 + y)/(1 - y)]$$

for X_5 and X_7 positive and ABS (y) less than one. Observe that T is invertible; in fact,

$$T^{-1}(z) = (az - b)/(az + b) \text{ for z positive}$$

Thus, f and g are equivalent and the values of f can be computed from the values of g and vice versa.

$$(T \circ f)(X_5,X_7) = g(X_5,X_7)$$

$$(T^{-1} \circ g)(X_5,X_7) = f(X_5,X_7)$$

The relationship between ND7 and R75 is illustrated in Figure 2. The important point is: Knowing the value of one index is equivalent to knowing the value of the other index, therefore the indices are equivalent for decision making.

The equivalence of TVI7 and R75 is shown as follows: Let k and p be real, and define the functions $G:(-1,1) \dashrightarrow (k-1,k+1)$ and $H:(k-1,k+1) \dashrightarrow (L,U)$ by

$$G(v) = v + k$$

$$H(w) = w[ABS(w)]^{p-1}$$

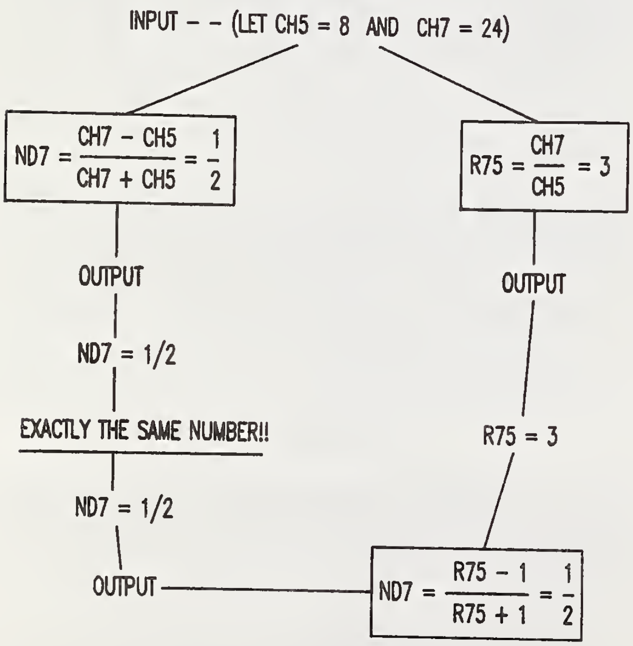

Figure 2. The equivalence of vegetation indices means the value of one index can be computed from the value of the other index. The flow chart outlines the computation of ND7 from R75.

for w between k-1 and k+1, $L = (k-1)[ABS(k-1)]^{p-1}$, $U = (k+1)[ABS(k+1)]^{p-1}$, for ABS(v) less than one, and 0/0 defined as 1. It is easy to verify that G and H are one-to-one and onto and that $(H \circ G \circ T^{-1} \circ g)(X_5,X_7) = (f(X_5,X_7) + k)[ABS(f(X_5,X_7) + k)]^{p-1}$. Taking k = p = 1/2 and a = b = 1 yields a one-to-one function between TVI7 and R75.

$$(H \circ G \circ T^{-1})\ R75 = TVI7$$

Another way to view VI equivalence is that equivalent VIs divide the DC space into the same set of equivalence classes. This interpretation is illustrated graphically in Figure 3.

EXAMPLE 2

This example illustrates the utility of VI equivalence in the context of alarm models. Suppose we take as our decision rule:

- o Sound a "warning bell" if ND 7 is above

$$B = 0.5$$

Using the relationships developed in Example 1, it is easy to see that equivalent decision rules based on R75 and TVI7 are:

- o Sound a "warning bell" if R75 is above

$$A = (1+B)/(1-B)=3.0$$

- o Sound a "warning bell" if TVI7 is above

$$C = ABS(B) + .05 = 1$$

Applying the hypothetical alarm model to spectral data taken in 1980-81 over a winter wheat field in Wilbarger

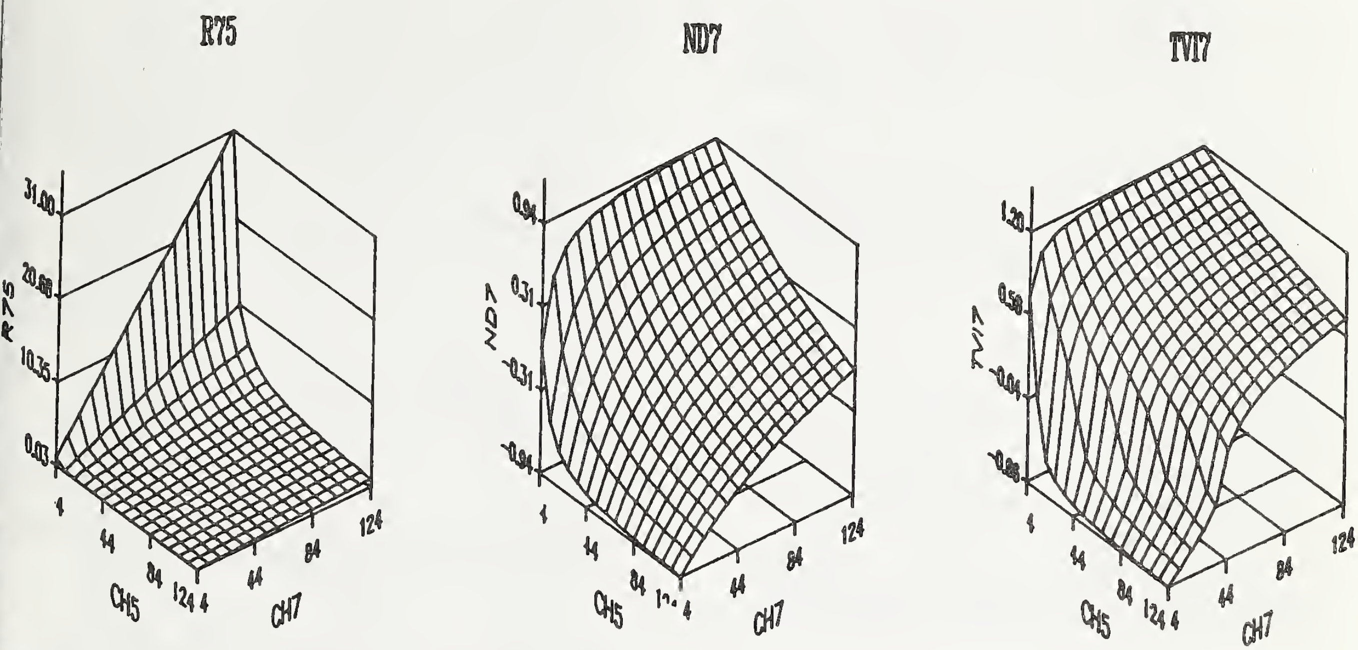

Figure 3. The response surfaces of R75, ND7, and TVI7 determine the same equivalence classes - the set of lines emanating from the origin in the two dimensional DC space.

County, Texas, one sees that precisely the same action is taken regardless of the decision rule used (Figure 4). The bell rang from November 17 through January 10.

SUMMARY AND CONCLUSIONS

Since the launch of Landsat 1 in 1972, investigators have derived numerous formulae for the reduction of multispectral scanner measurements to a single value for predicting and assessing vegetation characteristics such as species, leaf area, stress, and biomass. Part I of this paper summarized many of these formulae and the empirical relationships among them. Most formulae fall into one of two basic categories: Those that use ratios or those that use differences to exploit the spectral characteristics of soil and vegetation. Part II of this paper developed

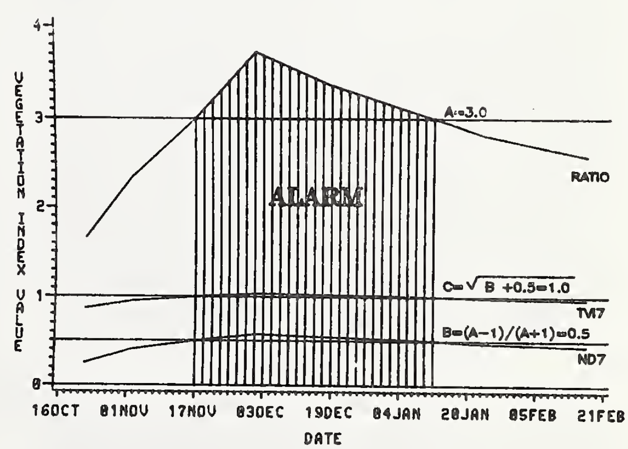

Figure 4. The hypothetical alarm model shows that no matter which VI is used exactly the same decision will be made. This illustrates that VIs can be equivalent for decision making and not have the same graph.

the idea of two vegetation indices being equivalent: two indices were taken to be equivalent, if the decision made on the basis of one index could have equally well been made on the basis of the other index. The significance of this idea was studied by example in several contexts and it was shown that for all practical purposes several widely used indices are equivalent.

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APPENDIX A
MODERN FUNCTION NOTATION

Almost as basic to modern mathematics as the concept of a set is the concept of a function. If A and B are sets, a function f from A into B is a rule which associates to each element x of A an element f(x) of B. If f is a function from A to B, one writes f: A-->B. If $x \varepsilon A$, then f(x) is called the value of f at x. Often functions are thought of as transforms or maps from one set into another. In today's terminology the terms "transformation", "mapping", and "operator" are synonomous with function. If f:A-->B and $x \varepsilon A$, then one says that f maps x to f(x). An example illustrate these concepts. Let A be any non-empty set. The function f:A-->A defined by f(a) = a for all a A is called the identity function and is denoted i_A.

If f:A-->B is a function, the set A is called the domain of f and the set B is called the range of f. A function is defined by specifying its value for each element belonging to its domain. Two functions f and g from A to B are said to be equal if f(x) = g(x) for all $x \varepsilon A$.

Suppose that g:A-->B and f:B-->C are functions. If $x \varepsilon A$, then we may define a function from A into C by first mapping x to f(x) and then mapping f(x) to f(g(x)). This function is called the composite of f and g and is denoted by f o g. According to the above definitions

$$(f \circ g)x = f(g(x))$$

Let f:A-->B be a function. Then f is said to be one-to-one if, f(x) = f(y) implies x = y. For example, if f:R-->R is the function f(x) = 5x + 3, then f is one-to-one, because 5x + 3 = 5y + 3 implies that x = y. The function g(x) = x^2 is not one-to-one, since g(3) = g(-3).

A function f:A-->B is said to be onto if, for every $y \varepsilon B$, there exists an $x \varepsilon A$ such that f(x) = y. For example, f(x) = 5x +3 is onto, since for every $y \varepsilon R$ one has f((y - 3)/5) = y. However, g(x) = x^2 is not onto, since there does not exist a real number x such that f(x) = -1.

If f:A-->B is one-to-one and onto, then for every $b \varepsilon B$, there is exactly one $a \varepsilon A$ such that f(a) = b. Therefore, one may define the function f^{-1}:B-->A by $f^{-1}(b)$ = a. The function f^{-1} is called the inverse of f. Clearly one has

$$f \circ f^{-1} = i_B \text{ and } f^{-1} \circ f = i_A$$

If f:A-->B and C is a subset of B, the set $[a \varepsilon A \mid f(a) \varepsilon C]$ is called the inverse image of C, and is denoted by $f^{-1}[C]$. The collection of all inverse images of the singleton set [b], as b ranges over B, partitions the set A into mutually disjoint sets. The individual members of this collection are called equivalence classes. For example, if r:R^+x R^+-->R is the function r(x,y) = x/y, the equivalence class $f^{-1}[b]$ = [(x,y) x/y = b] is the line emanating from the origin and having slope b^{-1}.

CHAPTER 15. APPLICATION OF WHEAT YIELD PROJECT INFORMATION TO FOREIGN AREAS

245 //

J. L. Rogers[1]

The Wheat Yield Project was initiated by ARS as a part of its effort in support of the Large Area Crop Inventory Experiment (LACIE). Two of the original Wheat Yield Project personnel were members of the Yield Advisory Group (YAG) assigned in support of the Yield Estimation System (YES) of the LACIE Project. LACIE was a joint NASA, NOAA, USDA project to develop remote sensing, sampling, aggregation and plant simulation technology to estimate wheat production in eight of the major wheat-producing countries of the world. Production estimation was to be done using the basic methodology of Area X Yield = Production.

Wheat simulation models developed as a part of the Wheat Yield Project have not been designed nor has a great effort been made to adapt the models to simulate wheat yields over a large area such as county, district or state. This does not mean that these models are not usable in estimating production over large area. The developed models give a yield prediction for a small area or plot. These yield estimates integrated with a defined sampling strategy can be used for yield and/or production estimation over a large area.

The wheat simulation models have several distinct components which are now being or can be used for foreign area crop condition assessment and yield and production estimation. These components include phenology tracking, soil water estimation, biomass estimators and evapotranspiration estimates as well as grain yield estimation.

Use of these model types in foreign areas requires a reliable daily meteorological data source for model operation. Data elements needed include temperature, precipitation and solar radiation. The U. S. Air Force (Cochrane, 1981) produces grid point (Hoke, et al., 1981) estimates of these data elements over selected areas of the world. These data are used operationally by USDA and Department of Defense (DoD) but the real accuracy of the grid point estimates has not been established.

NOAA is currently developing the capability (Tarpley, 1982) to produce gridded estimates of the required daily data from geostationary satellites in the western hemisphere and polar orbiting satellites in the eastern hemisphere. This technique development and subsequent data evaluation are being done as a part of the AgRISTARS Project.

Early warning model development has produced several useful models for foreign applications. Models for winterkill (Ravet, et al., 1979), wheat yield reduction (Ravet, et al., 1983) and wheat water and temperature stress (Ravet and Hickman, 1979) were developed as part of the LACIE and AgRISTARS Projects in cooperation with personnel of the ARS Wheat Yield Project. These models have been run operationally by the Foreign Crop Condition Assessment Division (FCCAD), Foreign Agricultural Service (FAS) since 1979. Output from these models is routine information sources for input into FAS regularly scheduled crop assessments.

The CERES-Wheat Model (Jones, et al., 1982) was run for the 1982 crop year for USSR winter and spring wheat at some 70 grid point locations to establish a baseline estimate for these grid points. USAF meteorological data

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were used as input to the model operation. During the 1983 crop year, these same 70 grid point locations were run biweekly in an operational mode and the outputs regularly furnished to FCCAD for their use in assessing USSR grain production. Results of this exercise are being evaluated by FCCAD at the present time. This assessment will be published in early 1984.

The development of a sampling and aggregation procedure for foreign crop production estimation along with the refinement of wheat yield estimation models and meteorological data estimation techniques will enhance the capability to estimate foreign wheat production. Wheat models and meteorological data estimation techniques available now can provide a routine information source for foreign crop condition assessment.

Expansion of the ARS Wheat Yield Project charter to cover spring wheat as well as winter wheat would be beneficial to foreign area applications.

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